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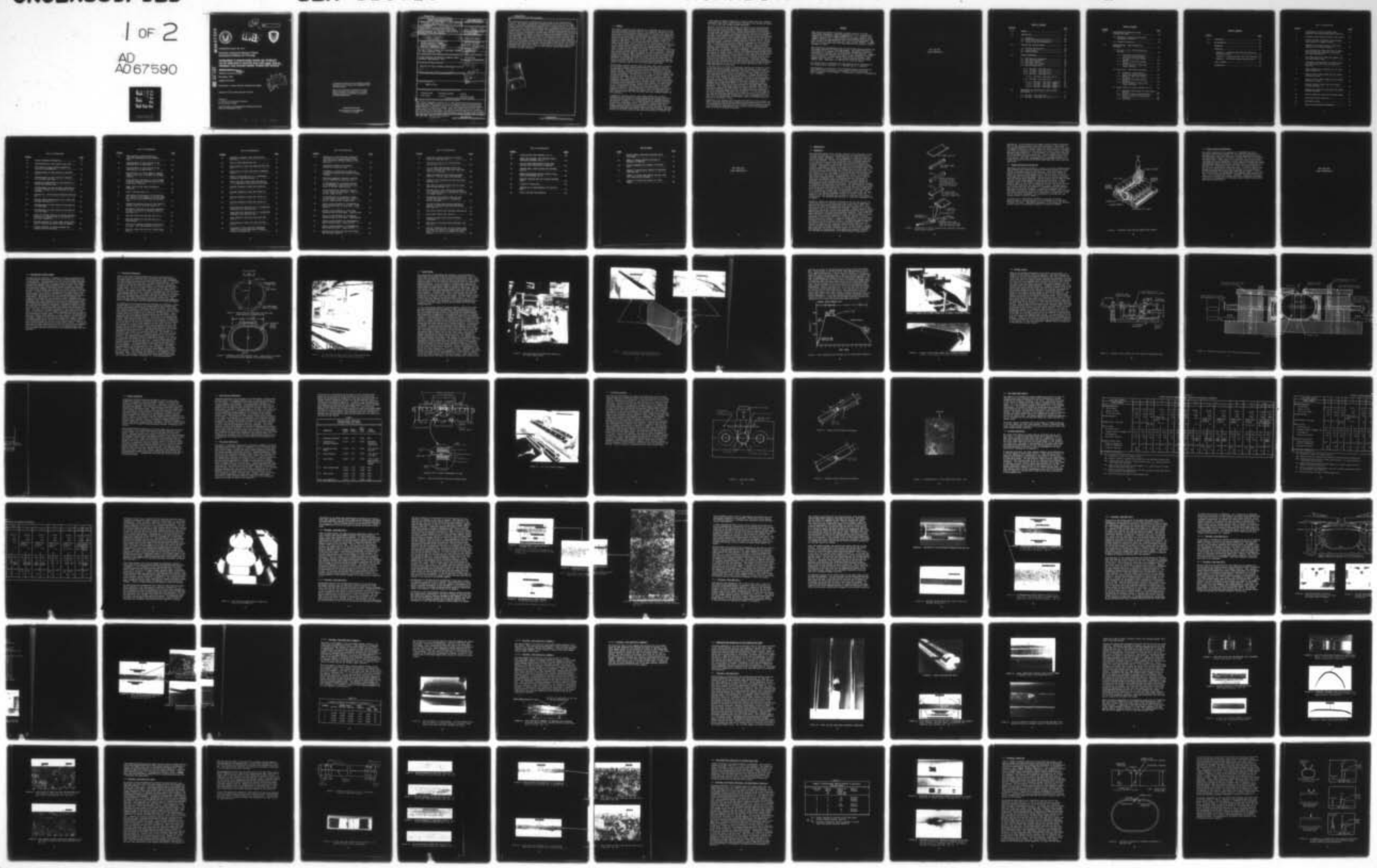

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Production Engineering Measures Program
Manufacturing Methods and Technology

ESTABLISHMENT OF MANUFACTURING METHOD AND TECHNOLOGY FOR THE FABRICATION OF HELICOPTER MAIN ROTOR BLADE SPARS BY CONTINUOUS SEAM DIFFUSION BONDING TITANIUM SHEET MATERIAL

SIKORSKY AIRCRAFT Division of UNITED TECHNOLOGIES
Stratford, Connecticut 06602

November 1978

AMMRC TR 78-50

Final Report - Contract Number DAAG-46-76-C-0016

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Prepared for
U.S. ARMY AVIATION R&D COMMAND
St. Louis, Missouri 63166

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes a series of U.S. Army sponsored Manufacturing Methods and Technology, MM&T programs which were ultimately aimed at evaluating and implementing into production the use of the Continuous Seam Diffusion Bonding, CSDB, process to fabricate reliable, lower cost titanium alloy 6Al-4V helicopter main rotor blade spars. The current production process for manufacturing the UH-60A Army BLACK HAWK helicopter main rotor blade spars uses a plasma arc weld to join a cold brake formed cylindrical shape titanium sheet pre-form.

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The titanium pre-form is subsequently creep formed to the required final contour. The subject program has investigated and fabricated various shape spar pre-forms and manufacturing operations that could be easily cold brake formed from flat titanium sheet material into a configuration that is capable of being continuous seam diffusion bonded and subsequently creep formed to the final contour. Tooling which is capable of clamping and satisfactorily bonding the selected configuration pre-form shape has been designed and constructed. Process parameters relating to bonding variables and material condition have been evaluated. The subject program has successfully diffusion bonded three, ten foot length BLACK HAWK spar tubes, and non-destructively inspected, NDI, the bonded spar tubes for any abnormalities. Finally, the fatigue characteristics of the diffusion bonded ten foot long spar design has been evaluated by full-scale and small-scale specimen fatigue testing, and found to be a viable manufacturing process which should be considered as an alternate fabrication procedure for blade spars as well as other similar joining applications on Ti-6Al-4V aircraft structures.

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1.0 SUMMARY

The overall objective of this program is to implement the use of Continuous Seam Diffusion Bonding, CSDB, for the production fabrication of the UH-60A BLACK HAWK Helicopter titanium alloy 6Al-4V main rotor blade spar. The program is a production oriented effort to establish and demonstrate CSDB as an alternate lower cost manufacturing process to the current production Plasma Arc Welding, PAW, Process. The program was originally planned in two phases. The goal of the present contract, Phase I, is to apply the CSDB process to the fabrication and evaluation of ten foot length tubular spars. Phase II which has not been initiated, was intended to scale-up and fabricate twenty-five foot long prototype spars. The Phase I effort has been completed and has demonstrated that CSDB is a viable alternate to the current PAW Process for producing main rotor blade spars or other similar aircraft structures. Phase I included: establishing a tubular pre-form shape and design that can be produced by cold brake forming and joined by CSDB; a parametric variation study to provide basic bonding tool concepts; determination of process controls and obtain basic parameters for bonding full-scale pre-forms; design and fabrication of tooling to accomplish CSDB of ten foot pre-forms into ten foot long spar tubes of good bond quality; and the non-destructive inspection, NDI, and physical testing of the ten foot diffusion bonded spar tubes.

Establishing a tubular pre-form shape and design that could be produced by cold brake forming titanium sheet material and joined by CSDB was accomplished by evaluating several pre-form configurations and tooling fixture designs. The evaluation was achieved by conducting a trade-off between cold brake forming limitations and cost, vs bonding equipment and tooling requirements. The objective of the trade-off was to minimize the tolerance requirements for the pre-form in order to minimize recurring production cost. This approach required that the bonding fixture would accommodate the maximum variation in the pre-form while still maintaining consistent reproducible high quality diffusion bonds. Once the pre-form configuration was established, titanium sheet material was brake formed to the selected pre-form shape, welded, and creep formed to an airfoil contour to demonstrate the ability of the selected shape to be creep formed successfully. Final modification to both the final pre-form configuration and to the bonding tool fixture was not accomplished until after actual hardware had been fabricated and trial bonding attempts had been performed.

A parametric variation study to prove basic bonding tool concepts, determine process controls and obtain parameters for bonding full-scale pre-forms was accomplished by investigating several bonding variables and material conditions. The bonding variables and material conditions selected for investigation were: the standard bonding conditions of speed, current, and force used successfully in previous work; the standard bonding conditions varying speed, current, and force; difference in material thickness; non-parallel edge fitup; edge roundness; and gap. Results of the study indicates that good joint quality is produced with

a wide range of standard conditions of current, speed, and force; however, nonparallel edge fitup, rounded corners, and gaps do not produce good quality joints even under optimum bonding parameters.

Based on the selected pre-form shape, the design of the tooling fixture, and the results of the process parameter study, titanium pre-forms were fabricated and diffusion bonded. Several modifications to the selected pre-form shape and changes in the tooling fixture design were incorporated as trade-off items before a satisfactory pre-form tube spar was finally produced. These modifications included symmetrical pre-forms with parallel top and bottom surfaces, and a variable height mandrel by the additions of shim material and the use of tantalum material as thermal strips. An optimization study to determine bonding conditions with the use of tantalum material thermal strips was also conducted on segments cut from one pre-form. The resultant modifications produced CSDB spar tubes of good bond quality. Non-destructive inspection of the diffusion bonded spar tubes included visual, borescope, fluorescent penetrant, radiographic, and ultrasonic methods. No evidence of voids, nonbonding, or lack of diffusion were detected in the bonded joint. However, an undesirable manufacturing defect was evident in several locations on the spar tubes away from the bond joint. The defect was produced by the interaction of the titanium pre-form with the tooling and appeared as a burnt spot in the tube which could be eliminated in the future by minor tool modifications. Subsequent fatigue testing of one full-scale ten foot long and twelve, nine inch long small-scale specimens indicated that the CSDB process produced fatigue properties which are adequate for use in critical dynamic applications such as the BLACK HAWK main rotor blade spar.

A follow-on Phase II effort to the present contract was intended to scale-up the facility and process to enable diffusion bonding of full length twenty-five foot long BLACK HAWK spars, and obtain a production cost basis. Additional qualification tests of sections of the full length spar were also proposed prior to a production commitment. Although encouraging results have been obtained in the current contract effort, pursuit of the follow-on or the originally proposed Phase II effort is not recommended at this time because of the following reasons: (a) A substantial capital investment has already been committed to production plasma arc welding equipment and a significant amount of full scale qualification data on plasma arc welded spars has now been obtained for the BLACK HAWK, UH60A helicopter. (b) A significant additional dollar commitment would still be required to scale-up the CSDB process to produce full-size, twenty-five foot long production spars and obtain the qualification data necessary to be able to incorporate CSDB spars into production. (c) The time frame of the existing production schedule for the UH60A helicopter with respect to that time at which CSDB spar implementation could be accomplished is such that it is not expected that a substantial return on investment would be realized at this point in time.

Regardless of the decision not to proceed with Phase II of the current contract, continuous seam diffusion bonding has been demonstrated to be a viable manufacturing process and should be considered as an alternate fabrication procedure for blade spars as well as other similar joining applications on Ti-6Al-4V aircraft structures.

PREFACE

This report was prepared by Sikorsky Aircraft, Division of United Technologies Corporation, under the sponsorship of U. S. Army Aviation Research and Development Command (AVRADCOM), St. Louis, Missouri, with technical monitor by U. S. Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts, under Contract DAAG46-76-C-0016. The Army technical contract monitor was Mr. Paul J. Doyle, DRXMR-ER, of AMMRC. This is the final report and voers work conducted from October 1, 1975 to September 30, 1978.

This project was accomplished as part of the US Army Aviation Research and Development Manufacturing Technology program. The primary objective or this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army material. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: US Army Aviation Research and Development Command, ATTN: DRDAV-EXT, P.O. Box 209, St. Louis, MO 63166.

The authors wish to acknowledge the contributions and the cooperation of the following Solar personnel: A. G. Metcalfe and E. C. Thorsrud.

Acknowledgement is also given to the following Sikorsky individuals for their efforts and assistance in the mechanical testing and material analysis portions of this program: C. Matusovich, R. Scott, M. Koronkiewicz and A. Thompson.

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2.0 INTRODUCTION

2.1 Background

The continuing demand of the aerospace industry in the production of more efficient aircraft has led to the extensive use of titanium alloys for critical aircraft components. These components are often very large with intricate shapes and contours, and may represent a significant cost element of the aircraft. In order to minimize cost of titanium components, it is essential to exploit both design, and manufacturing methods and techniques which conserve titanium and reduce the cost of hardware fabrication. Considerable effort in this area has been expended by Sikorsky Aircraft, especially as related to helicopter main rotor blade spars. The original method of manufacturing the titanium main rotor blade spar for the H-53 helicopter was to begin with a 4,000 pound titanium billet, forge and extrude it into a 3,400 pound 33 foot hollow tube, and then machine and creep form it into the desired aerodynamic contour. The finished spar weighed only 206 pounds. Because the cost of titanium is high and there is a considerable amount of machining required, this method of fabrication is extremely costly and impractical. Several methods of producing lower cost titanium spars have been evaluated extensively. These methods include canning the extrusion, cold forming and hot forming of extrusions, and sheet metal construction. The most economical of these processes and the present method used by Sikorsky Aircraft for manufacturing titanium main rotor blade spars is by joining cold brake formed sheet metal by plasma arc welding, PAW. Titanium sheet is cold brake formed to a circular shape, joined along its longitudinal seam by PAW, and creep formed into the desired aerodynamic contour in a heated ceramic die. A composite cover and honeycomb core is added to obtain the final airfoil configuration. The manufacturing operation is illustrated diagrammatically in Figure 1.

Plasma arc welding was selected by Sikorsky as the low risk solution for joining the seam in the titanium blade spar on the YUH-60A, UTTAS prototype aircraft subsequently identified as the UH-60A, BLACK HAWK. This selection was based on information and experience available in 1971 when the aircraft was in its initial stage of design. Looking forward to future production requirements, several early Manufacturing Method and Technology, MM&T programs were initiated and successfully completed. These early programs successfully evaluated Continuous Seam Diffusion Bonding as a potential lower cost, reliable alternate to plasma arc welding. The major advantages of CSDB is that the process is accomplished in air with minimal process controls as compared to plasma arc welding which requires an inert atmosphere and numerous process controls. An added advantage to CSDB is the relative ease in inspection of the flat diffusion bonded joint as compared to inspection of a contoured irregular shape weld bead. In an initial evaluation program, Reference (a), two 10 foot D-shaped simulated spar shapes were hot formed, diffusion bonded, and full-scale and small-scale specimens fatigue tested. This testing was extremely successful and confirmed the acceptability of the CSDB process for this type of

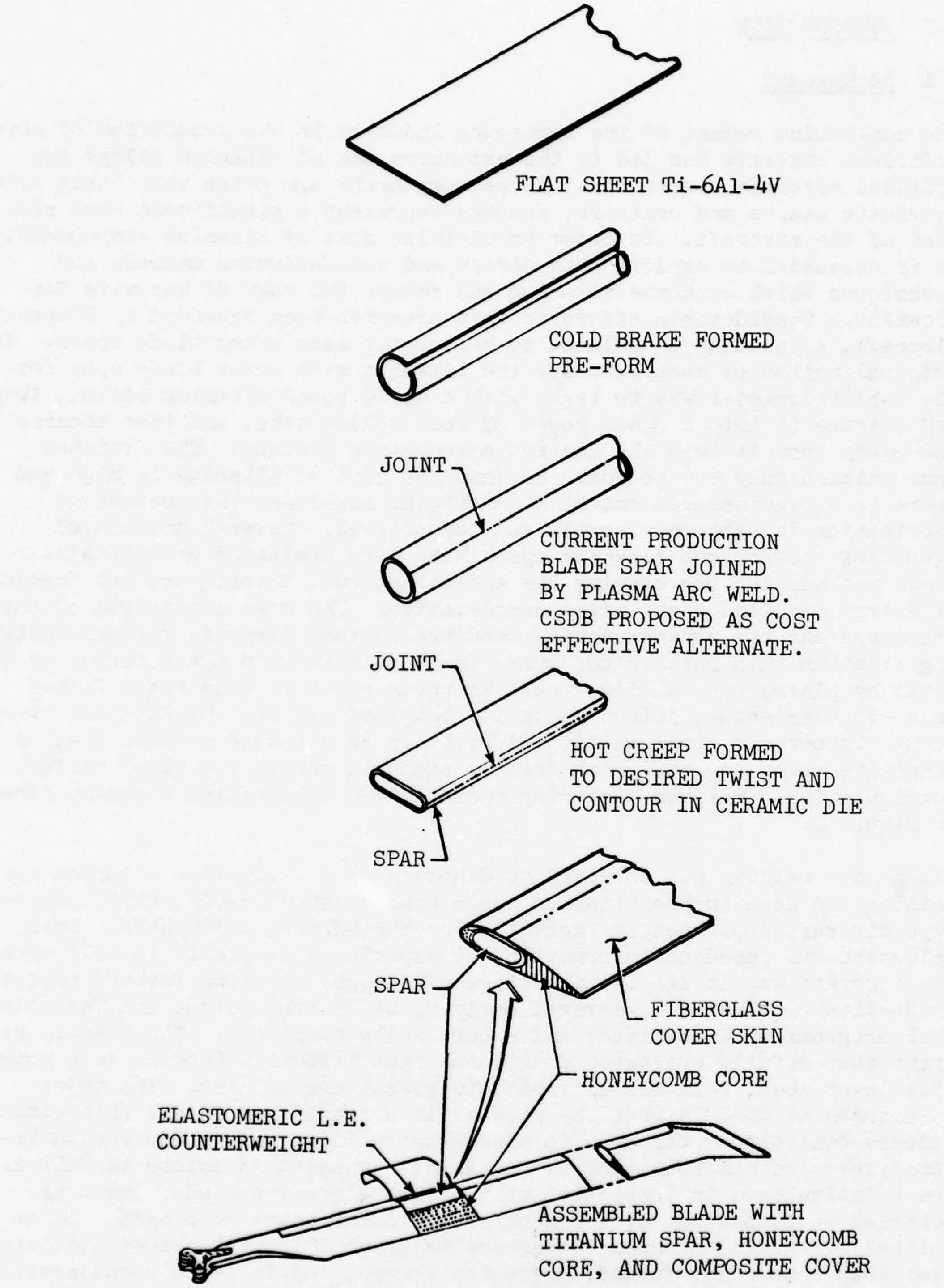

FIGURE 1. ILLUSTRATION OF TYPICAL TITANIUM SPAR COMPOSITE COVER BLADE MANUFACTURING OPERATION.

application. In the Reference (b) program, process variables associated with the CSDB operation were defined and investigated. The results of this program demonstrated that good quality is produced with a wide range of standard conditions of current, speed, and force; however, as expected, poor fitup and contamination could produce poor quality joints even under optimum bonding parameters. In the Reference (c) program, NDI techniques were investigated and several evaluated. Results indicated that "state of the art" NDI techniques could be utilized to evaluate diffusion bond joint quality. With this encouragement the present MM&T program was initiated and aimed directly at the UH-60A BLACK HAWK main rotor blade spar application.

2.2 Process Description and History

Continuous seam diffusion bonding is a simple, solid state bonding process that involves local electrical resistance heating of material to a temperature considerably below its melting point. Sufficient pressure is applied to achieve intimate contact and diffusion of atoms across the joint, thus creating a metallurgical bond. The work piece is mounted on a carriage with an internal mandrel serving as one electrode and passes under an external wheel electrode. Current flowing from the wheel through the joint to the backup mandrel provides localized heating. Joining pressure normal to the bondline is obtained when the locally heated material under the wheel trys to expand and is restrained by the friction of the wheel surface and the rigid external tooling. Carriage speed, wheel current and force are adjusted to accommodate different materials, part type, and material thickness. A closed loop feedback control of temperature and pressure provides repeatability of bonded joints and makes the process suitable for production. The process is accomplished in air with no protective atmosphere. An illustration of the CSDB spar and tooling concept is shown in Figure 2.

Solar Division of International Harvester, San Diego, California, developed CSDB in 1965 and applied it to the fabrication of many small titanium structures. Significant development of the process was achieved and the process was subsequently applied to production hardware.

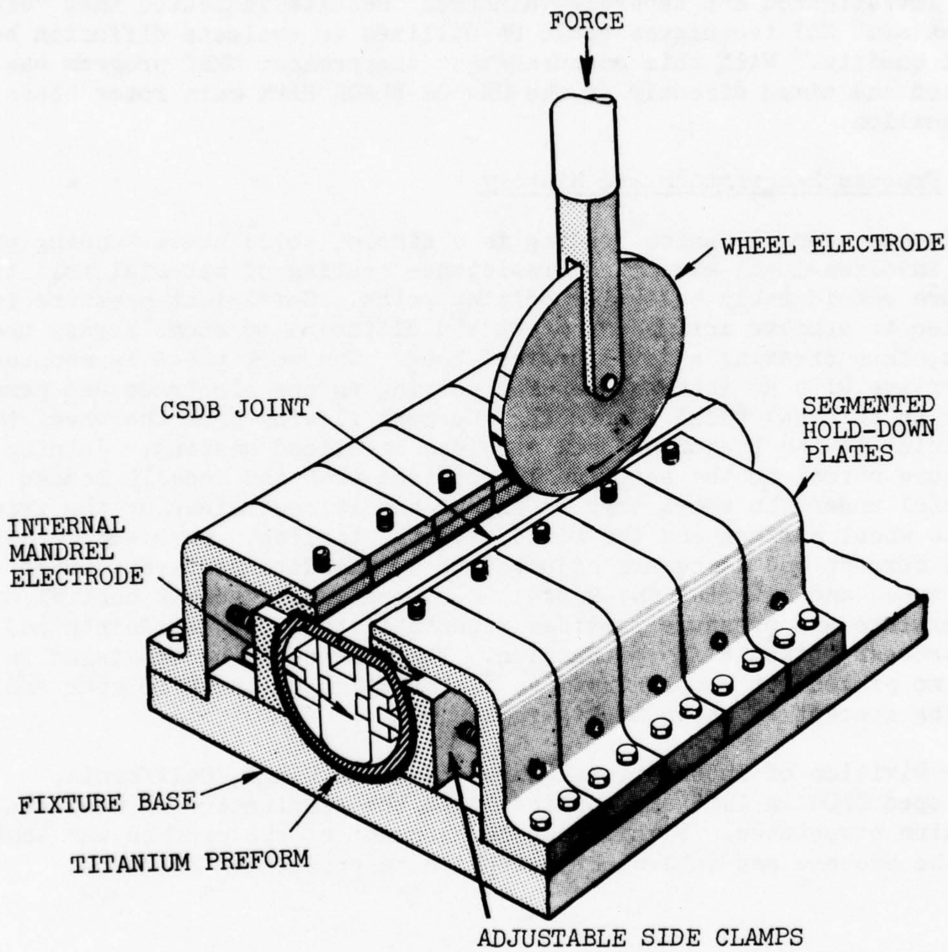

FIGURE 2. CONTINUOUS SEAM DIFFUSION BONDING SPAR CONCEPT.

2.3 Program Scope and Methodology

The overall objective of this program is to implement the use of continuous seam diffusion bonding for the production fabrication of helicopter main rotor blade spars as a low cost manufacturing process. The program was planned as a production oriented task with an integrated two-phase effort. Phase I was to be a relatively low cost risk reduction stage which would establish the brake form titanium sheet pre-form configuration; process parameters; tooling capable of bonding Army UH-60A, BLACK HAWK helicopter type ten foot long spar tubes; non-destructive inspection, NDI, technique for CSDB spar tubes; and physical testing of the ten foot long diffusion bonded spar tubes. This first phase of the program was accomplished with Solar as Sikorsky's prime subcontractor providing Sikorsky with maximum CSDB technology and support. Phase II was to scale-up the tooling equipment to accommodate fabrication of full-size, 25 foot prototype spar tubes. Subsequent inspection and fatigue testing was to provide the necessary data base to determine the production cost for implementation of continuous seam diffusion bonding BLACK HAWK spars into production.

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3.0 PRE-FORM AND TOOLING CONCEPT

An evaluation was conducted to establish a pre-form configuration and a tooling fixture design that could produce a CSDB titanium spar tube of high quality. The requirements for the selected pre-form configuration entailed the capability of being produced by cold brake forming titanium sheet material and subsequently joined by CSDB. The requirement for the selected tooling fixture design included the capability of positioning, clamping, and holding the cold brake formed titanium pre-form in such a manner that the pre-form could be joined by the CSDB process. In order to obtain an adequate pre-form shape and a tooling fixture design, the evaluation consisted of a trade-off between cold brake forming limitations and cost, and bonding equipment and tooling requirements. The objective of the trade-off was to minimize the tolerance requirements for the pre-form in order to minimize recurring production cost. This approach required that the bonding fixture would accommodate the maximum variation in the pre-form configuration while, still maintaining consistent reproducible high quality diffusion bonds. The final pre-form design was elliptical in shape and symmetrical about the centerline of the titanium sheet with parallel top and bottom surfaces. The final tooling concept was based on the final pre-form selection. The bonding tool fixture consisted of a base plate with fixed vertical side blocks, side vice clamps, segmented hold-down top plates, and an adjustable internal mandrel. Once the pre-form configuration was finalized, titanium sheet material was brake formed to the selected pre-form shape, plasma arc welded along its longitudinal length to simulate a diffusion bonded joint, and hot creep formed to an airfoil contour. This task demonstrated the ability of the selected pre-form shape to be creep formed successfully to the required airfoil contour. It should be noted that the final modifications to both the final pre-form configuration and the bonding tool fixture were not accomplished until after actual hardware had been fabricated and trial bonding attempts had been performed.

3.1 Pre-form Configuration

Prior to the brake forming operation the titanium sheet material is milled and ground to specified width, thickness, and length dimensions. The sheet width must be milled such that the required spar circumference will meet drawing tolerances after the CSDB joining operation. The edges of the flat sheet must be milled at a specific angle such that after forming to the pre-form shape the edges to be joined are perpendicular to each other. The milled, butted surface to be joined also requires a surface finish of 100 AA or better. After milling, the edges are not deburred. The square, sharp, knife edges are required in order to obtain a good quality diffusion bond. Rounded or chamfered edges can lead to a non-acceptable CSDB joint. The square, sharp, knife edges of the titanium sheet are subsequently protected with vinyl edge strips during storage and during cold brake forming into the pre-form configuration. The strips are only removed for chemical cleaning of the spar and immediately prior to loading the spar into the tooling fixture for diffusion bonding.

A preliminary pre-form specification was developed and forwarded to Solar, the CSDB vendor, as a guide for the design study of the equipment modification and bonding tool necessary to bond the pre-forms. The preliminary approach consisted of cold brake forming the titanium sheet material into a round tubular shape pre-form with a flat surface at the top of the pre-form where the pre-form is to be joined by the CSDB method. Figure 3 shows the initial proposed preliminary design pre-form shape illustrating areas that would require control. Upon review of the proposed preliminary design pre-form shape by Solar, a second pre-form configuration evolved. This second pre-form configuration was elliptical in shape with a flat surface at the top of the pre-form, at the diffusion bond location, and at the base of the pre-form, opposite the bond joint location. The flat surface at the base of the pre-form was incorporated in order that the pre-form and internal mandrel could be easily positioned within the bonding fixture prior to bonding. Further modifications to this elliptical shape pre-form resulted in a final design configuration that is symmetrical with parallel top and bottom surfaces. The symmetry of the pre-form consist of the vertical centerline at the base of the pre-form coinciding with the bondline or projected bondline at the top of the pre-form. This symmetrical shape is advantageous because it will assist in the loading and clamping of the pre-form in the bonding tool and will contribute to a better quality spar tube. A sketch of the symmetrical pre-form elliptical shape with parallel top and bottom surface is provided in Figure 4. The specification of the final design configuration and requirements is provided in Section 10.1, Appendix A. The brake forming operation was accomplished on a 1000 ton hydraulic press brake, Figure 5. The titanium sheet was initially brake formed at the ends to the 90° position. The sheet was then formed to an intermediate elliptical formed shape. Final forming was completed to the symmetrical configuration. The procedure establishing the actual brake forming operation is described in detail in Section 4.5, "Pre-form Fabrication".

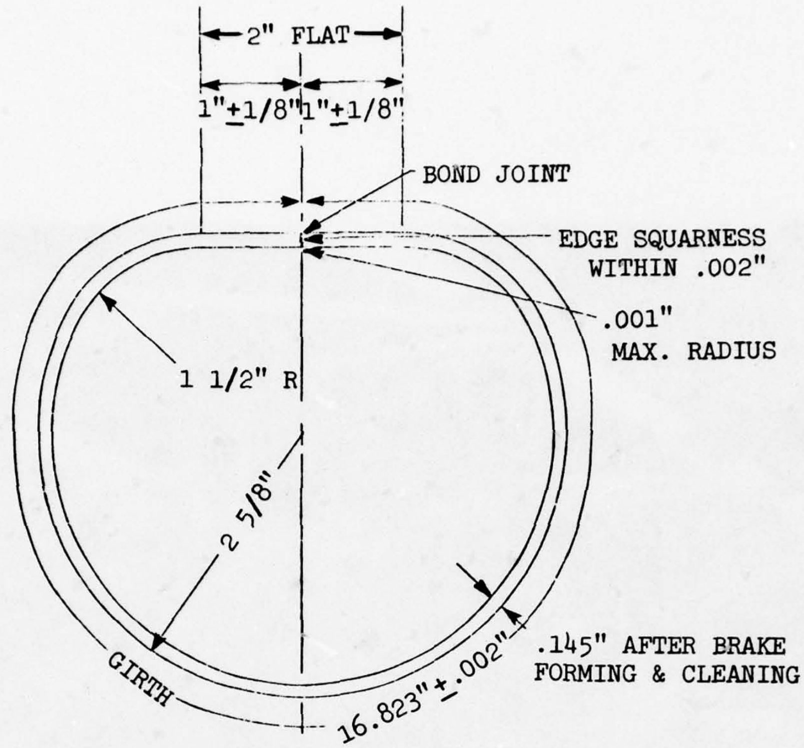


FIGURE 3. INITIAL PROPOSED PRELIMINARY PRE-FORM SHAPE.
CROSS SECTION IN CLAMPED POSITION.

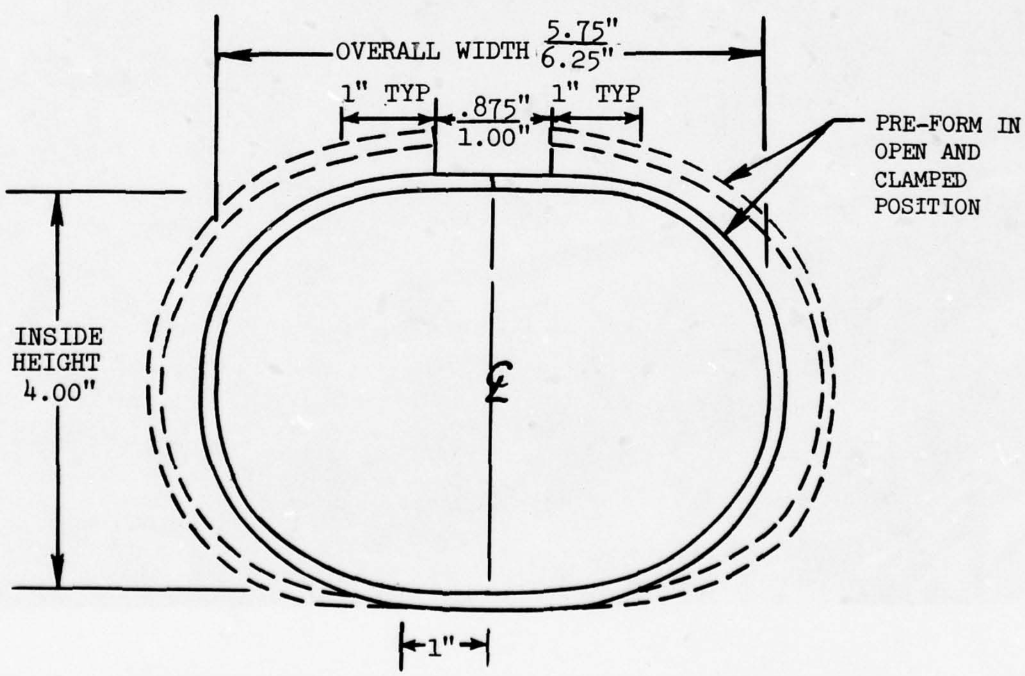


FIGURE 4. SYMMETRICAL PRE-FORM ELLIPTICAL SHAPE; CROSS SECTION IN CLAMPED AND OPEN POSITION WITH PARALLEL TOP AND BOTTOM SURFACES.

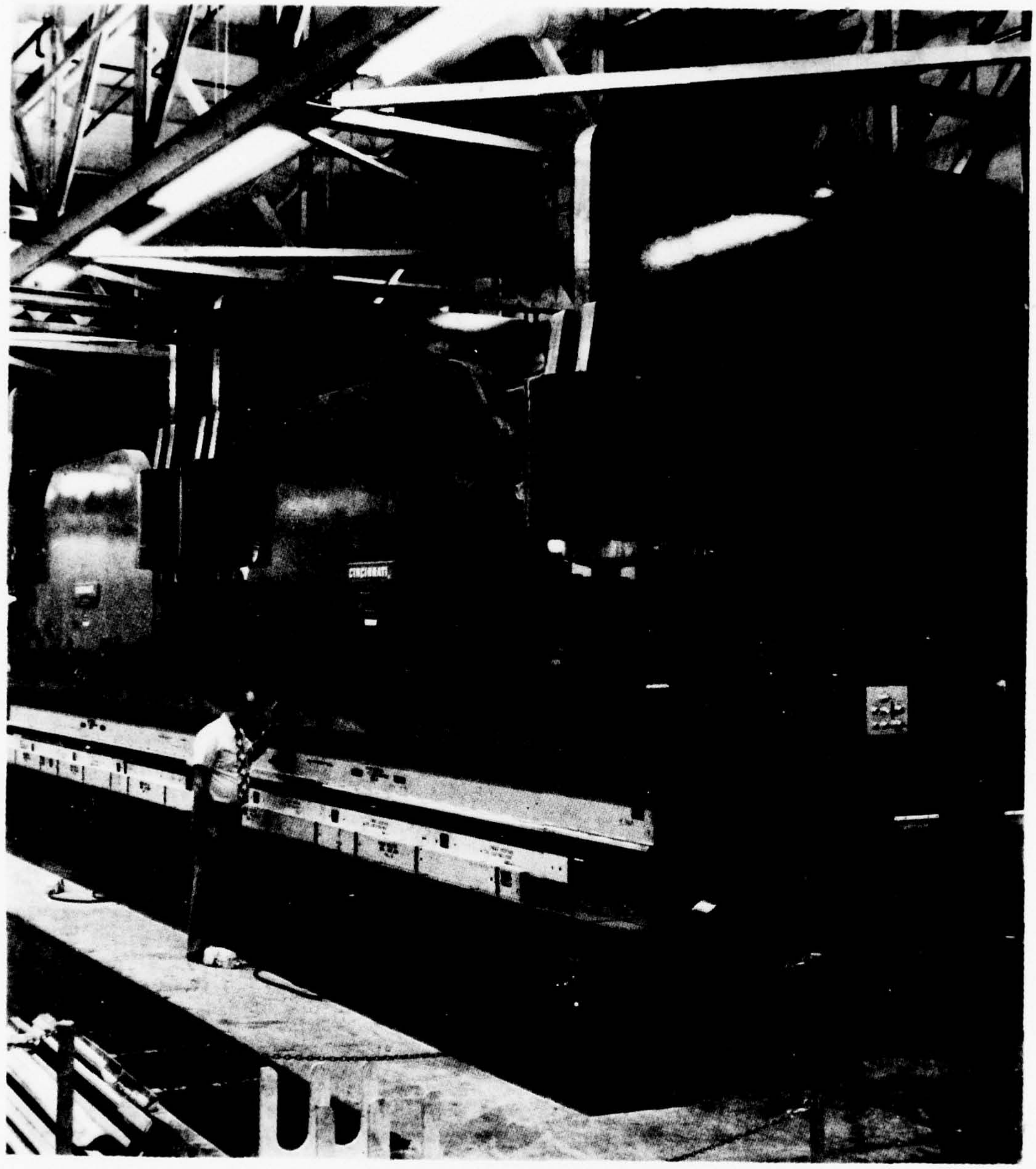


FIGURE 5. 1000 TON HYDRAULIC BRAKE PRESS USED TO BRAKE FORM TITANIUM SHEET MATERIAL INTO DESIRED PRE-FORM CONFIGURATION.

3.2 Creep Forming

Once the pre-form configuration was finalized, it was necessary to verify that the selected elliptical pre-form configuration could be creep formed successfully to the required finished airfoil shape. The ability to creep form the elliptical shape was questionable until demonstrated because of the flat areas in the pre-form which are required for diffusion bonding. A six foot length of titanium sheet material was brake formed to the selected elliptical pre-form shape and plasma arc welded along its longitudinal length to simulate a CSDB joint. The six foot joined pre-form was hot creep formed to the BLACK HAWK blade contour and twist in the BLACK HAWK production ceramic die creep forming press, Figure 6. Initially, the joint is located along the flat area of the short axis of the ellipse. After creep forming, the joint is located at the long axis of the airfoil shape. The tube shape is creep formed from a six inch by four and one quarter inch (6" x 4¼") ellipse to a one and three quarter inch by seven and one-half inch (1-3/4 x 7-1/2") airfoil shape. The operation is illustrated diagrammatically in Figure 7 with the change in cross section before and after creep forming depicted.

The hot creep forming operation involved chemical cleaning the joined pre-form, sealing the ends by welding on caps, connecting an access tube for pressurizing the internal cavity, attaching restraining lugs for use to align the tube in the die, protecting the assembly against high temperature contamination, and forming the pre-form to the desired contour in a heated ceramic die. Cleaning the joined pre-form entails soaking it in an alkaline bath, and acid etching it in nitric-hydrofluoric solution. Conical titanium caps are manually plasma arc welded to both ends of the joined pre-form to seal the internal area allowing it to be pressurized with Argon during the hot forming operation. An access tube is connected to one of the end caps providing a means for pressurizing the cavity. Restraining lugs are welded to the external tip of each conical cap and are used to position the joined pre-form in the ceramic die. The sealed, joined pre-form, with the end caps, access tube, and restraining lugs is coated with an inert Turco film. This film helps protect the external surface of the tube from elevated temperation oxidation during the hot creep forming operation. The assembly is placed, positioned, and aligned in the ceramic die hot forming press and purged internally with Argon. The assembly is pressurized internally with Argon to 25 psi during the first two hours heat-up cycle. Upon reaching the required $1335 \pm 35^{o}F$, the joined pre-form is straightened in the die cavity, the internal Argon pressure is increased to 50 psi, and the creep forming cycle is initiated. Actual creep forming of the joined pre-form to the airfoil contour is achieved in approximately one hour at the creep forming rate of 0.1 inch per min. Subsequent to creep forming the joined pre-form, the assembly is stress relieved. The stress relief is performed at the same temperature of $1335^{o}F$ with an increase of internal Argon pressure to 65 psi for two hours. After the two hour stress relief cycle, the heat to the creep forming press is shut off and

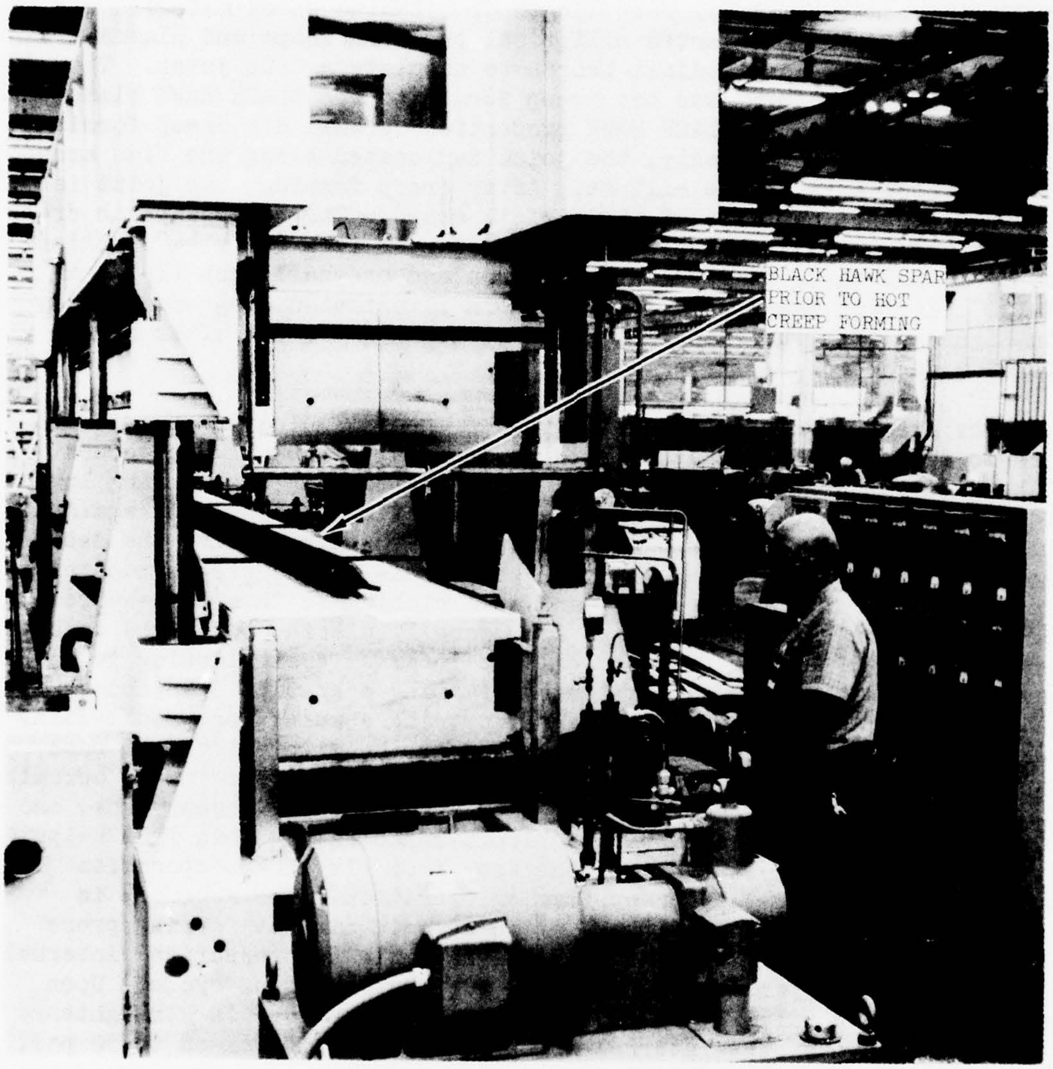


FIGURE 6. BLACK HAWK MAIN ROTOR BLADE SPAR CERAMIC DIE HOT CREEP FORMING PRESS.

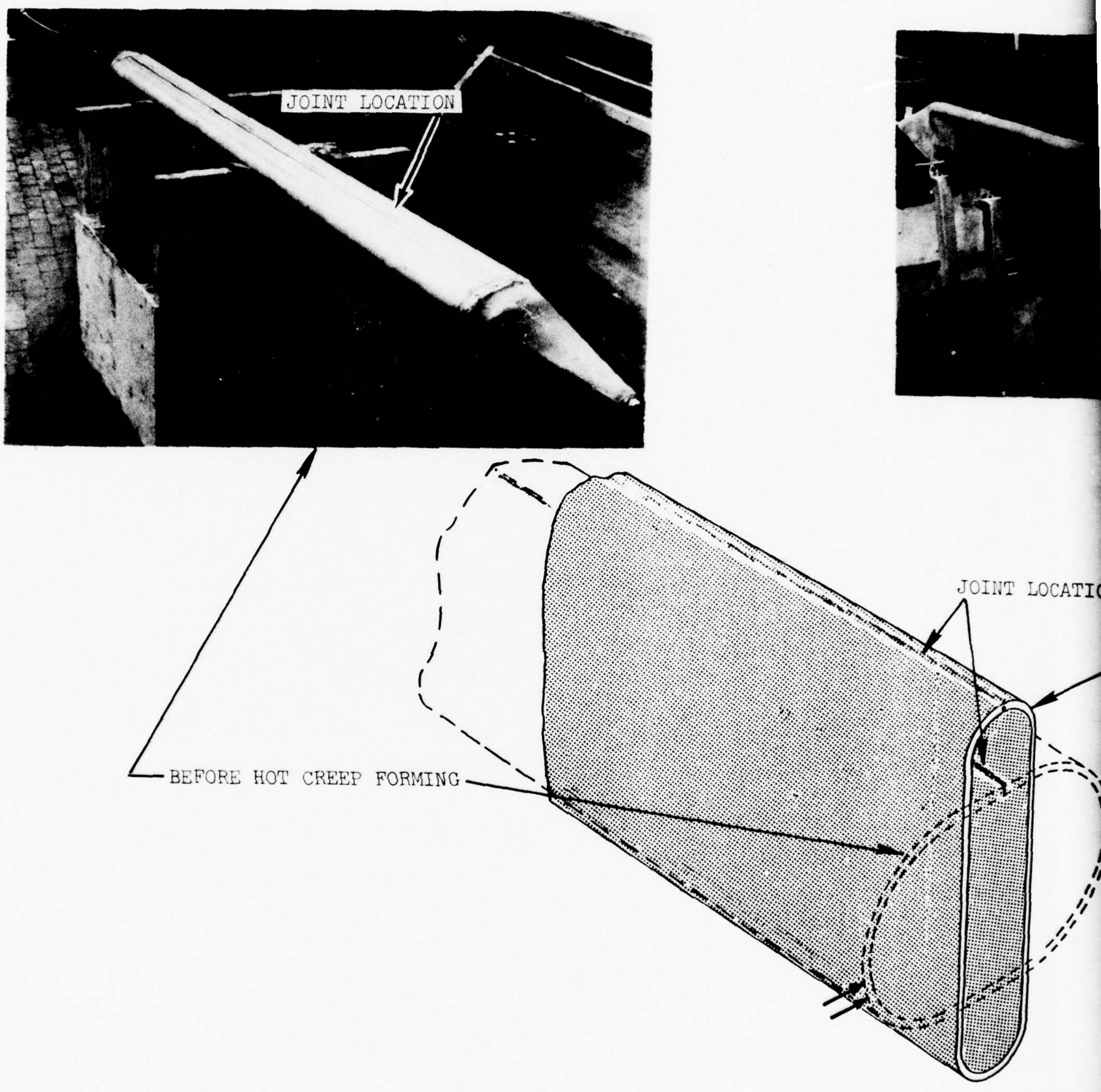
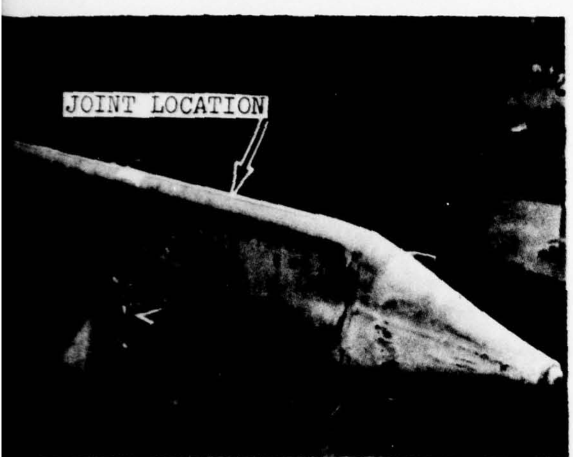


FIGURE 7. SIX FOOT ELLIPTICAL SHAPED TITANIUM PRE-FORM, BEFORE AND AFTER HOT CREEP FORM OPERATION.



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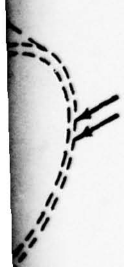
AFTER HOT CREEP FORMING



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the fans are turned on, initiating forced cooling of the creep formed spar. When the spar is cooled to 800°F, after approximately six hours, it is removed from the die. A Kolene hot salt solution is utilized to remove the inert film and any scale. Figure 8 illustrates a temperature, time, and pressure relationship during the creep forming operation. The spar is subsequently acid etched in nitric-hydrofluoric removing .001 to .002 inches of material from each surface to eliminate any minute layer of alpha case that could have formed during the hot creep forming operation. The tube contour and bow were inspected on the production template fixture and found to be satisfactorily within production drawing requirements. Figure 7 portrays views of the six foot tube spar before and after the creep forming operation. Note that the joint is located at the short axis of the ellipse before creep forming and on the long axis of the ellipse after creep forming. Figures 9 and 10 show the creep formed spar on the contour inspection fixture depicting its satisfactory conformance. This creep forming operation successfully demonstrated the ability to creep form the selected elliptical pre-form configuration to the required finished BLACK HAWK spar contour.

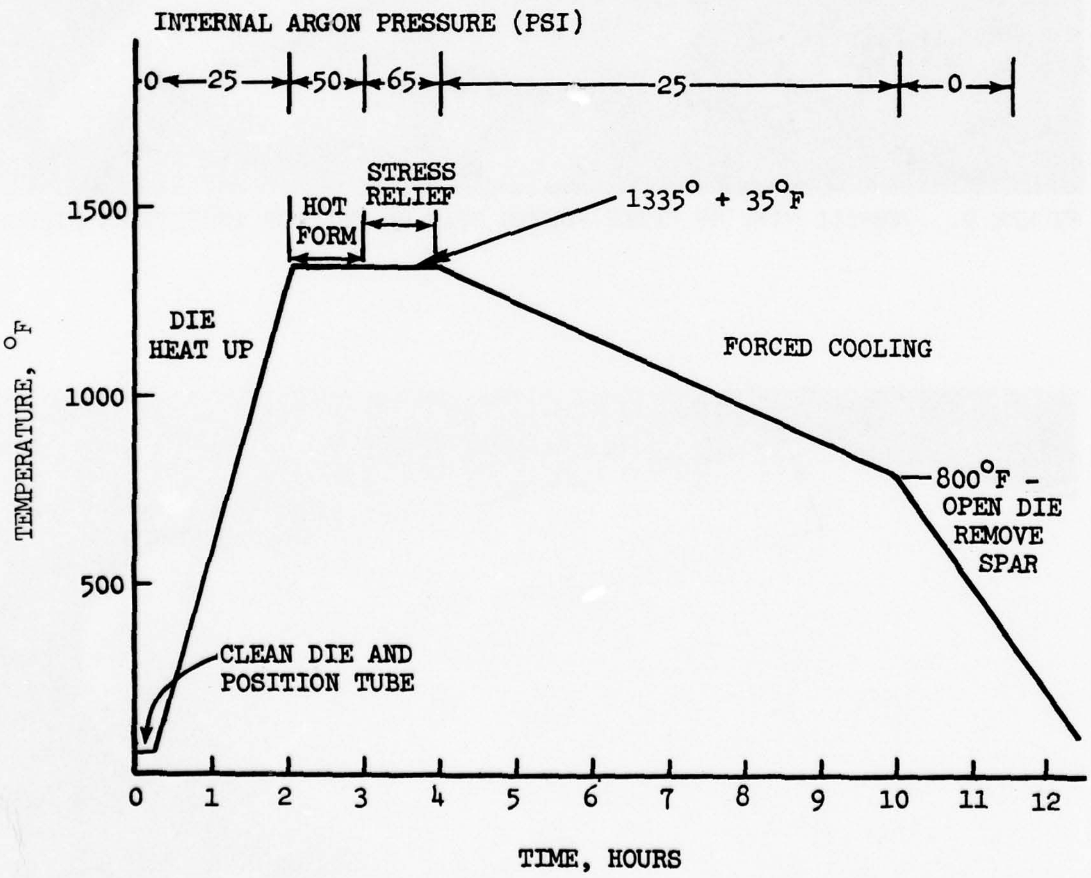


FIGURE 8. TIME, TEMPERATURE AND PRESSURE PLOT OF CREEP FORMING OPERATION.

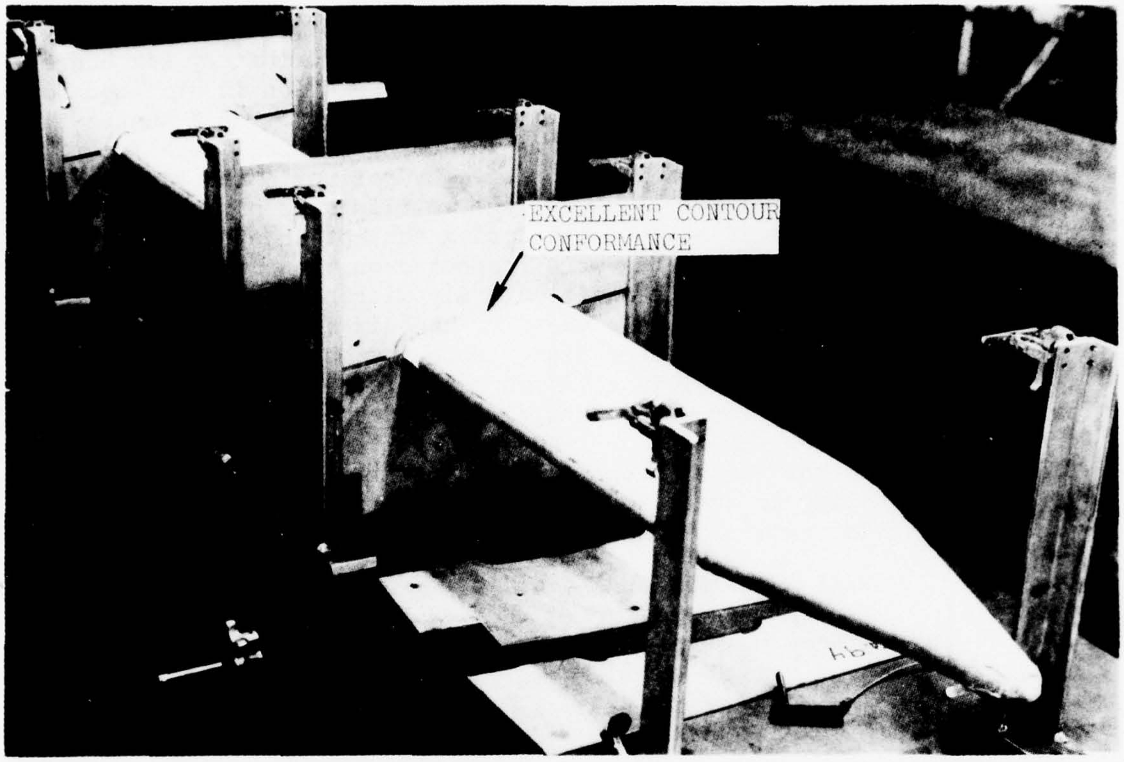


FIGURE 9. OVERALL VIEW OF CREEP FORMED SPAR ON CONTOUR INSPECTION FIXTURE.

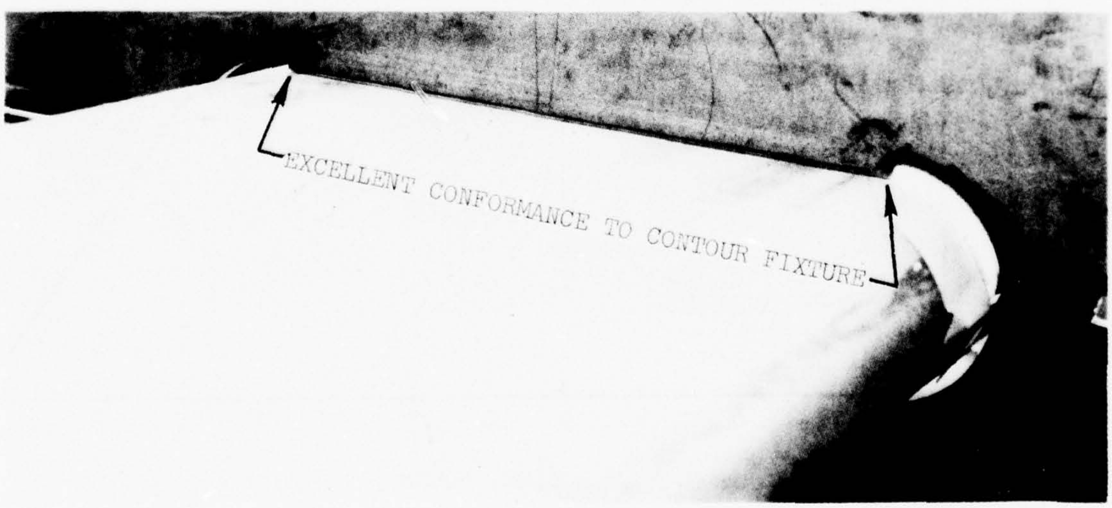


FIGURE 10. CLOSE-UP VIEW OF CREEP FORMED SPAR ON CONTOUR INSPECTION FIXTURE. NOTE EXCELLENT CONFORMANCE TO CONTOUR FIXTURE.

3.3 Tooling Concept

Based on the proposed preliminary round tubular pre-form shape, the original tooling design concept was prepared. The tooling design consisted of a two inch thick aluminum base plate with four inch wide aluminum fixed vertical side blocks; one fixed and one adjustable, one inch thick steel side vise clamps; sixteen, half-inch thick by nine inch wide by twelve inch long segmented steel hold-down top plates; and a twelve foot long by one inch wide by six inch high internal mandrel unit consisting of steel and copper components. Clamping and positioning of the pre-form within the tooling fixture was originally intended to be accomplished with cam-action type clamps and fast traverse vise assemblies. The internal mandrel unit was initially a fixed height dimension. A sketch of the original tooling concept is provided in Figure 11. Upon review of the original tooling design concept, it was concluded that greater flexibility of the bonding fixture was needed. This increase in flexibility was required in order to accommodate a wider range of tolerances in the pre-form shape which would allow fabrication at lower cost. The primary change in the tooling design involved adjustment capability for both sides of the fixture, i.e., the fixed steel vice clamp was made movable. Other changes included replacing the cam-type clamps with bolts to insure intimate contact of the butt joint to be bonded and to secure positioning of the pre-form onto the internal mandrel. The internal mandrel was changed to a rectangular shape cross section in order to accommodate the flat bottom of the elliptical shape pre-form and from a fixed height to a variable height unit by the addition of shim material to the base of the rectangular shape section. The contact points on the side vice clamps were repositioned to maintain positive clamping during bonding. A sketch of the final tooling concept is provided in Figure 12. A detailed explanation of the CSDB process has previously been described in the Section 2.2, "Process Description" together with an illustration of the CSDB spar concept, Figure 2.

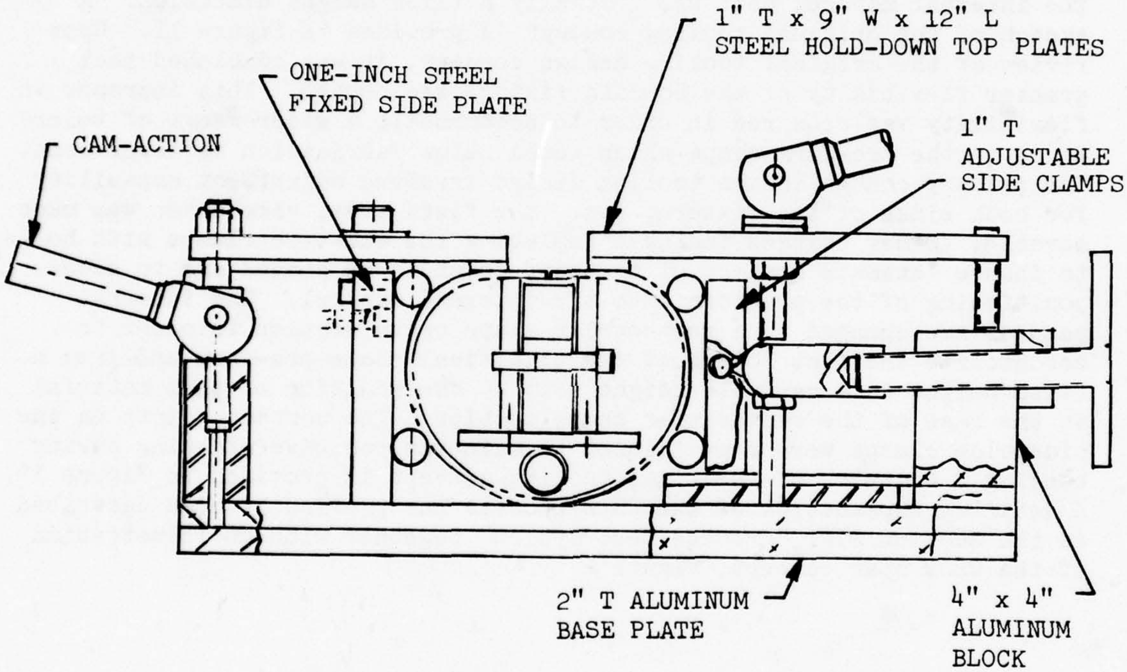


FIGURE 11. ORIGINAL TOOLING CONCEPT FOR CSDB CIRCULAR TITANIUM PRE-FORMS.

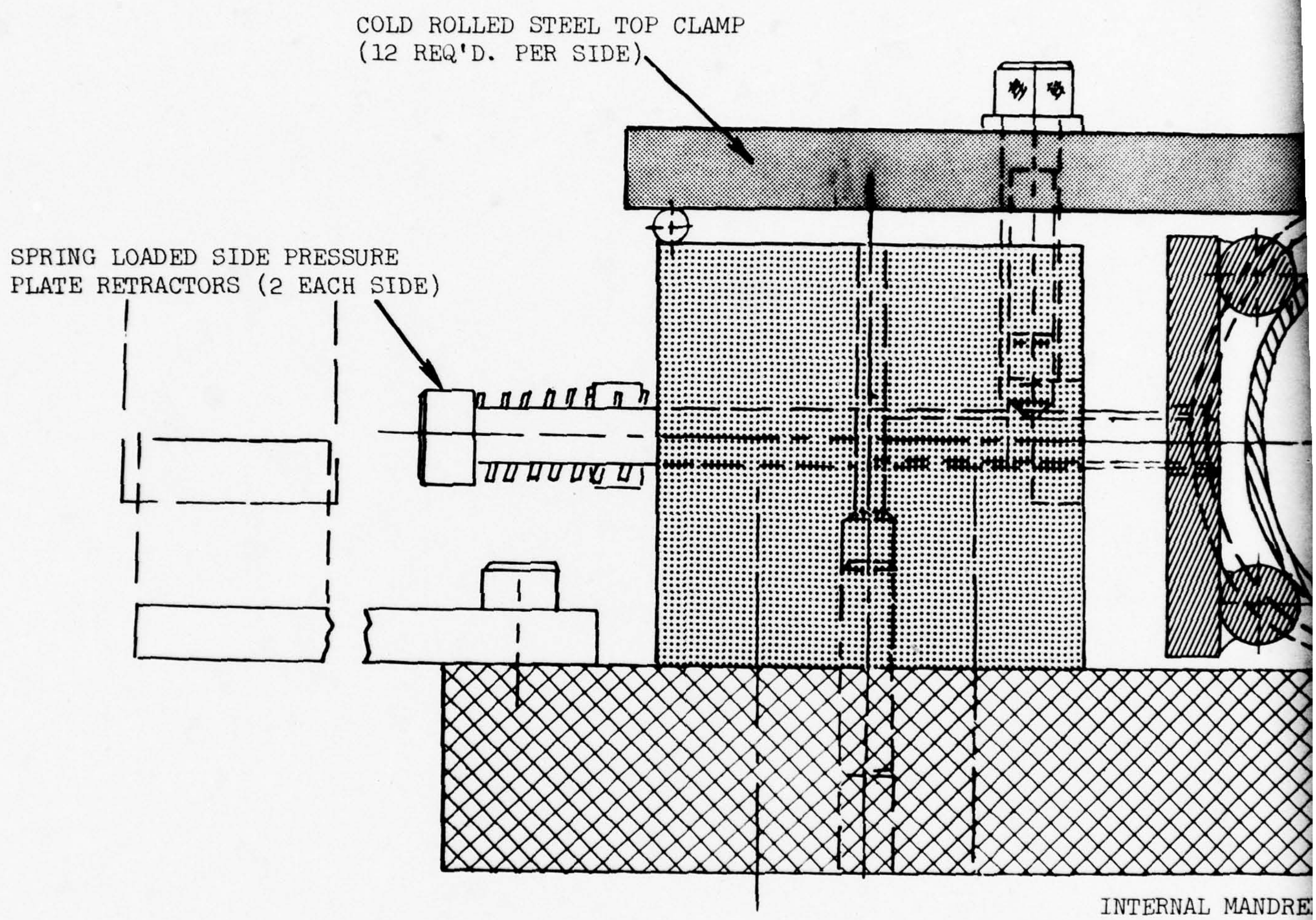
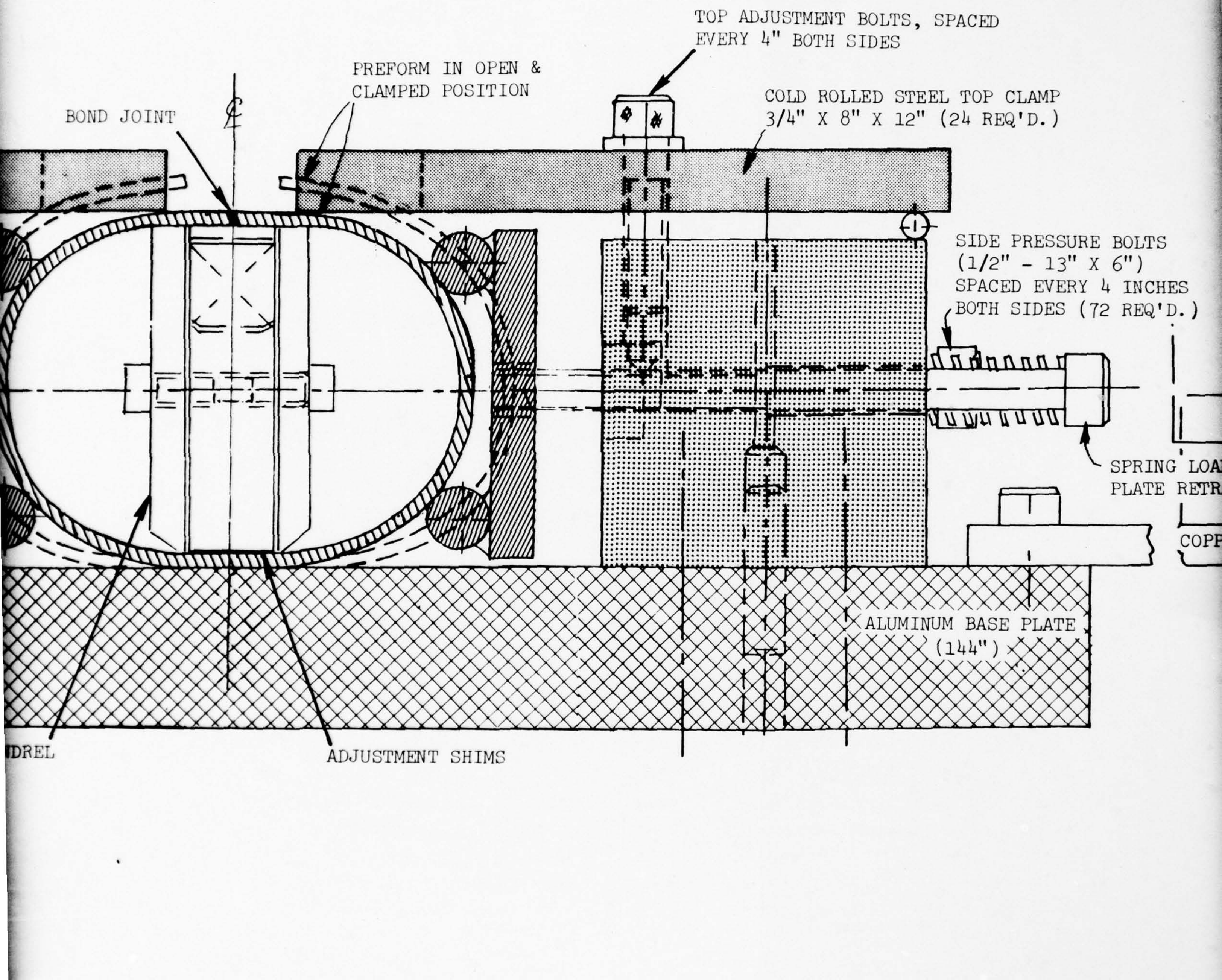
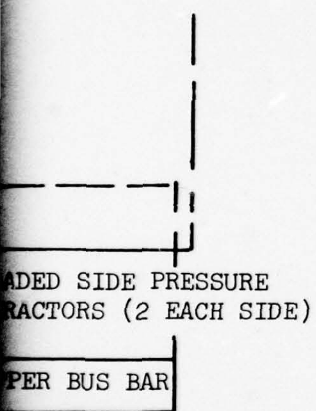


FIGURE 12. BONDING TOOL DESIGN FOR CSDB ELLIPTICAL SHAPE TITANIUM PRE-FORM.


TOP ADJUSTMENT BOLTS, SPACED EVERY 4" BOTH SIDES
PREFORM IN OPEN & CLAMPED POSITION
COLD ROLLED STEEL TOP CLAMP 3/4" X 8" X 12" (24 REQ'D.)
BOND JOINT
SIDE PRESSURE BOLTS (1/2" - 13" X 6") SPACED EVERY 4 INCHES BOTH SIDES (72 REQ'D.)
SPRING LOAD
PLATE RETRA
COPP
ALUMINUM BASE PLATE (144")
DREL
ADJUSTMENT SHIMS


ADED SIDE PRESSURE
RACTORS (2 EACH SIDE)
PER BUS BAR

4.0 PROCESS PARAMETERS

A parameter variation study was performed in order to prove basic bonding tool concepts, determine process controls, and obtain parameters for bonding full-scale pre-forms. Initially, the study was performed on flat sheet stock and later on three foot lengths of actual spar pre-form segments. The bonding variables and material condition selected for investigation were: small variations in the standard bonding conditions of speed, current, and force (head pressure) which were used successfully in previous work; differences in thickness of the material; nonparallel edge fitup of the material thickness dimension; edge roundness of the material; and gap, distance between surfaces to be bonded. Results of the study on the flat sheet stock indicated that good joint quality is produced with a wide range of standard conditions of current, speed, and force; however, difference in material thickness, nonparallel edge fitup, rounded corners, and gaps do not produce good quality joints even under optimum bonding parameters and must be carefully controlled.

Using nominal standard conditions of current, speed, and force with what was considered to be optimum conditions of material thickness, fitup, square corners, and no gap, four, 139-inch pre-forms were initially bonded. Although various minor changes in tooling and pre-form tolerances were sequentially made after each bonding operation, only limited success was achieved. After further investigation, it was determined that insufficient transfer of heat from the wheel electrode through the steel thermal strip to the pre-form was the major cause of the limited success. Therefore, an additional study was conducted on four, three-foot length of pre-form segments using tantalum thermal strips in place of steel thermal strips used in all of the previous work. The tantalum material permitted more efficient heat transfer from the wheel electrode to the area to be joined. This more efficient transfer of heat subsequently produces greater forging action which improved the quality of the bond to a satisfactory level. Arrangements were finalized to bond full-scale 139-inch pre-forms.

4.1 CSDB Facility Preparation

Prebonding preparation was performed on the CSDB machine, bonding wheel, bonding fixture and consumable details prior to loading and bonding of the test panels. The CSDB machine was functionally inspected to insure proper performance and response. The bonding wheel was checked for alignment with the machine table, establishing that the wheel face was parallel with the table and that the plane of the wheel (side) was at right angle to the table. The right angle of the wheel to the table was visually checked with a tool maker square when the wheel is loaded at the pre-established bonding pressure. The location of the bonding fixture is established with reference to the bonding table and the bonding wheel. The centerline of the bonding fixture and/or component to be joined was positioned to the centerline of the thickness or width of the wheel. This was accomplished visually with the aid of a pointer attached to the bonding wheel while the fixture is traversed from start to finish with the wheel in the up position. Initially, the bonding fixture is completely disassembled and vapor degreased. Only a dry lubricant, such as spray graphite is used when reassembling the fixture. Prior to each bonding operation, the fixture is wiped with methyl ethyl ketone, MEK, dried by a clean air blast and recoated with spray graphite. The consumable items, metallic thermal barrier, back-up bars, and thermal strips are cut to length, vapor degreased, and graphite coated; the molybdenum and titanium foils are cut to length and hand wiped with MEK in preparation for loading into the CSDB facility with pre-form to be bonded.

4.2 Flat Panel Fabrication

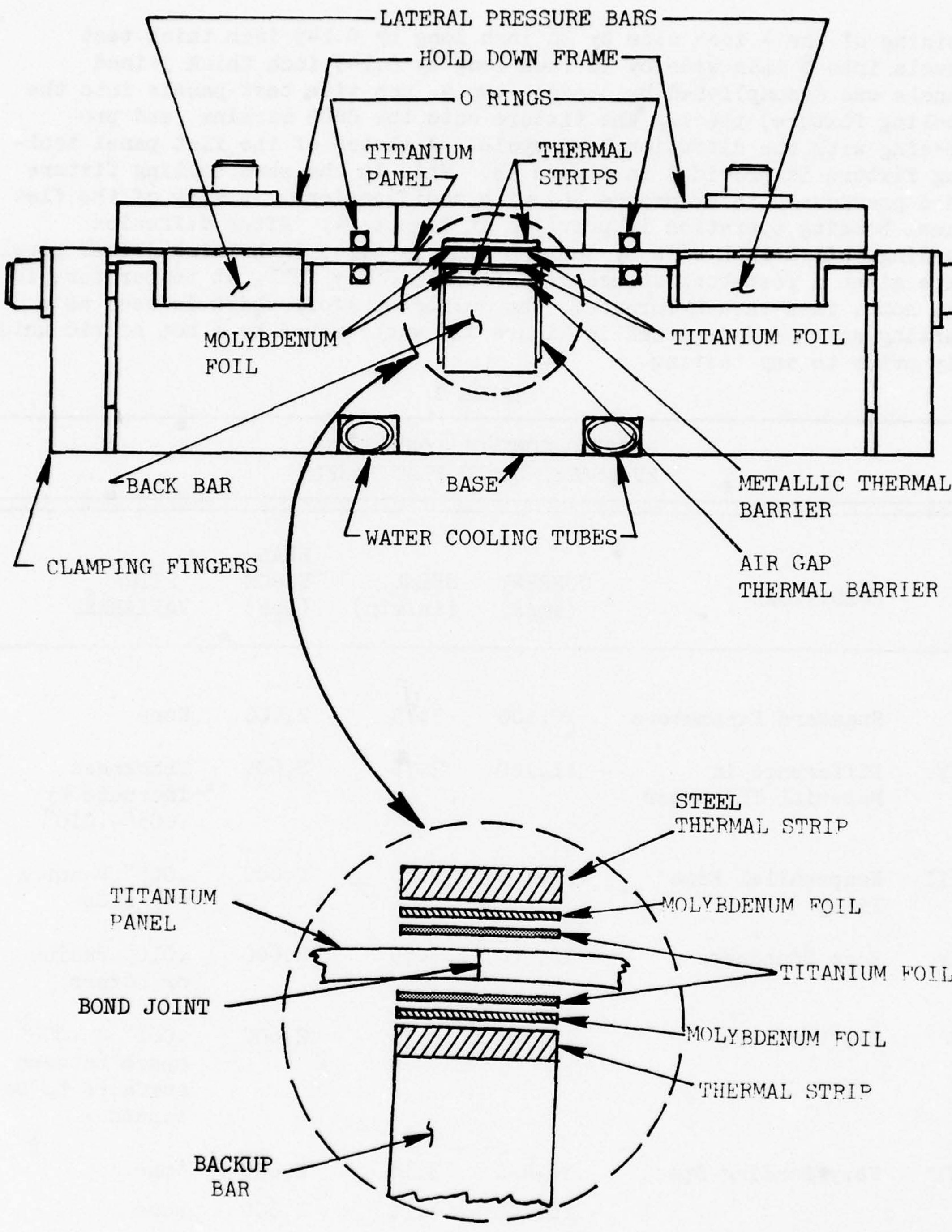
Test panels of annealed titanium alloy 6-Aluminum, 4-Vanadium, Ti-6Al-4V conforming to MIL-T-9046, Type III, Composite "C" with fine grain alpha-beta microstructure, 4 inches wide by 36 inches long by 0.145 inch thick were joined by CSDB incorporating several process parameter conditions. The process parameter conditions used were: standard parameters, difference in material thickness, nonparallel edge fitup, edge roundness, gap variations, and variations in bonding speed, current, and head force. The incorporated conditions are listed in Table I. Material preparation for CSDB requires machining of the edges to be joined and cleaning. Machining was accomplished as a standard milling operation, creating square, straight edges for the butt joint. Cleaning was performed just prior to bonding in order to insure mating surfaces chemically free from contamination. The panels were solvent washed with MEK to remove mill marks and other forms of ink or dye deposits. Immersed in hot, 160-180^{o}F alkaline degreaser for five minutes to eliminate any grease or oil. Subjected to nitric-hydrofluoric acid solution 70-140^{o}F for ten to fifteen seconds to loosen oxide and scale. Dipped in nitric acid solution, ambient temperature, to remove smut and other oxide reside, followed by a final air-water blasting. Details of the cleaning procedure are provided in Section 10.2, Appendix B.

Joining of the 4 inch wide by 36 inch long by 0.145 inch thick test panels into 8 inch wide by 36 inch long by 0.145 inch thick joined panels was accomplished by loading two 4 inch wide test panels into the tooling fixture, placing the fixture onto the CSDB machine, and proceeding with the diffusion bond cycle. A sketch of the flat panel tooling fixture is provided in Figure 13. This is the same tooling fixture used previously in Reference (b) with modifications. A view of the flat panel bonding operation is provided in Figure 14. After diffusion bonding, all 8 inch wide by 36 inch long by 0.145 inch thick joined panels were given a post-bond stress relief of 1350°F ± 25°F, at temperature for one hour, in a vacuum furnace. The molybdenum foil which is used as a parting agent and depicted in Figure 13, was removed by a hot nitric acid dip prior to any testing.

TABLE I

PROCESS CONTROL CONDITIONS
EVALUATED USING FLAT PANELS

	CONDITIONS	CURRENT (amps)	SPEED (in/min)	HEAD FORCE (lbs)	FITUP VARIABLES
I	Standard Parameters	10,500	3.75	2,600	None
II	Difference in Material Thickness	11,100	3.75	2,600	Thickness increase by .005"-.010"
III	Nonparallel Edge Fitup	11,100	3.75	2,600	.005" V-notch top side
IV	Edge Roundness	10,500	3.75	2,600	.010" radius or corner
V	Gap Variable	10,500	3.75	2,600	.001" & .002" space between surfaces to be bonded
VI	Vary Bonding Speed	10,400	3.18	2,600	None
		10,100	4.30	2,600	None
VII	Vary Current	10,800	3.75	2,600	None
		11,400	3.75	2,600	None
VIII	Vary Head Force	11,100	3.75	2,800	None



EXPLODED VIEW OF STACKUP ARRANGEMENT FOR CSDB

FIGURE 13. TOOLING FIXTURE FOR CSDB FLAT TITANIUM PANELS.

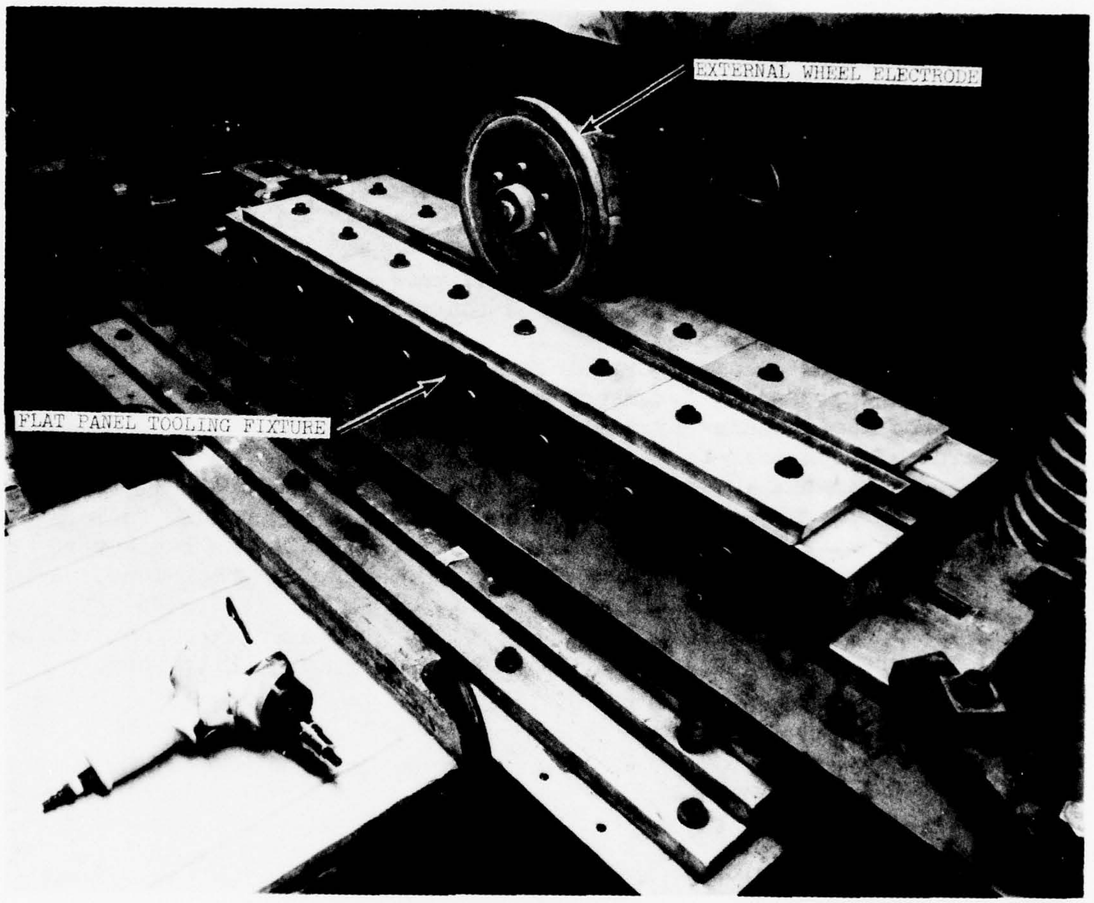


FIGURE 14. FLAT PANEL BONDING OPERATION.

4.3 Flat Panel Testing

Bond quality was determined by means of test specimens from each panel. Physical bend test, mechanical fatigue and tensile properties, and metallurgical examination were performed. In the bend test, a 1-3/4 inch diameter bar subjected the specimen to bend radius of 5.52 times the coupon thickness. Specimens were one inch wide and testing was performed with the surface nearest the bonding wheel contacting the 1-3/4 diameter bar. This method results in the maximum outer fiber tensile strain occurring on the joint surface farthest from the external bonding wheel electrode. A sketch of the bend test fixture is shown in Figure 15. This fixture was utilized in the previous Reference (b) program, and was also used in bend tests of specimens from the CSDB spar tube. Tensile tests were performed using an Instron testing machine. Ultimate tensile strength, 0.2% offset yield strength, and elongation were determined. The specimen configuration shown in Figure 16 conforms to ASTM E8 test method. A portion of the 0.005 inch thick titanium foil on both sides of the joint was removed during fabrication of the specimen. Fatigue test specimens were fabricated with a reduced cross section to induce failure at the joint. Specimen configuration is depicted in Figure 17. The specimens were rigidly mounted in a support block as a simple cantilever beam and vibrated at their resonant frequency by means of a Calidyne 1500 pound force electrodynamic shaker system. The specimens were deflected to a strain level of 0.5% peak-to-peak. The level of strain corresponds to 0.100 inch. Specimen tip deflection was measured and controlled throughout the test. This strain and deflection was chosen to produce failure in 10^4 to 10^7 cycles. Metallographic examination of all the bonds were conducted. Specimens were prepared using one etch-polish technique. A standard etch of two minutes Kroll's etchant, 2% HF, 3% HNO_3, 95% H_2O, plus four seconds 10% HF, 40% HNO_3, 50% H_2O has been used throughout this program. Figure 18 depicts a microstructure of a good quality bond.

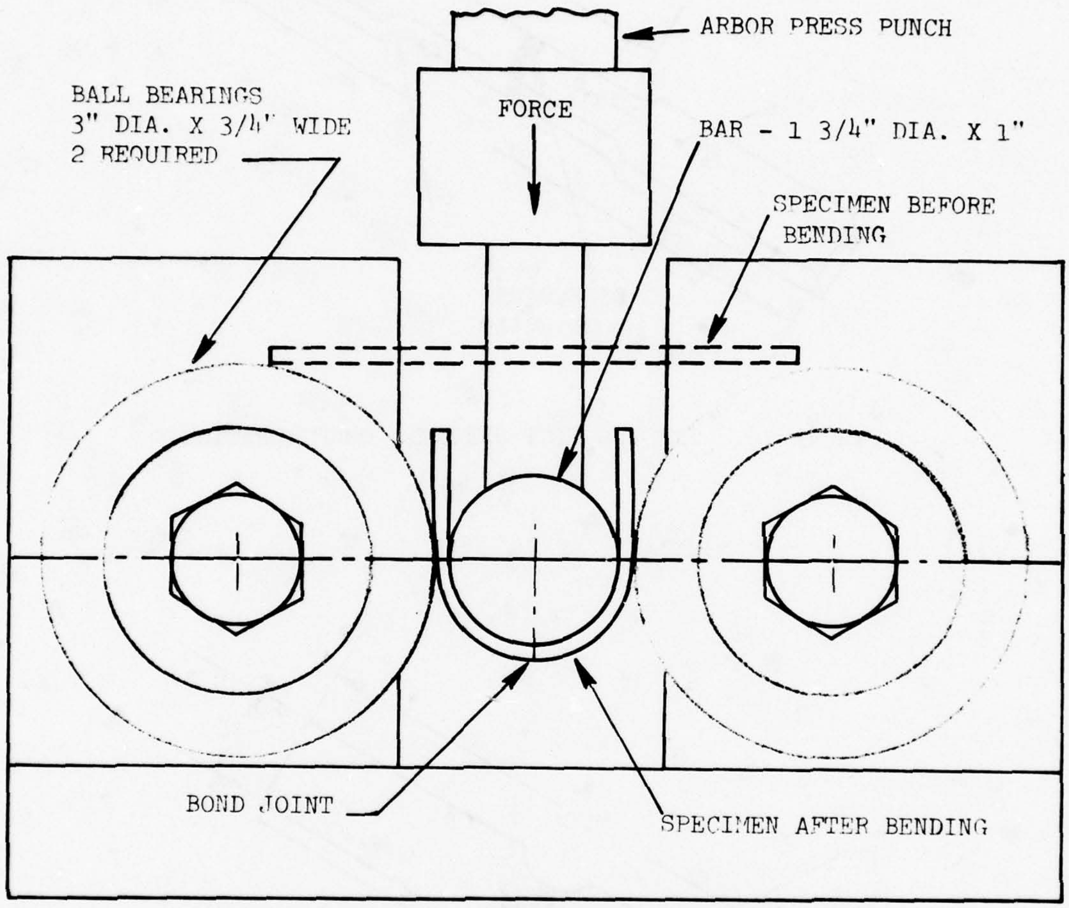


FIGURE 15. BEND TEST FIXTURE.

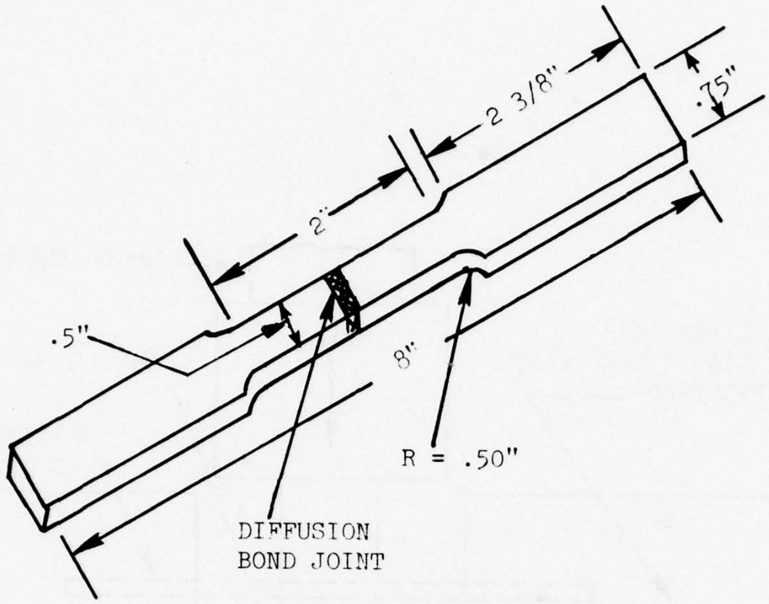


FIGURE 16. TENSILE TEST SPECIMEN CONFIGURATION.

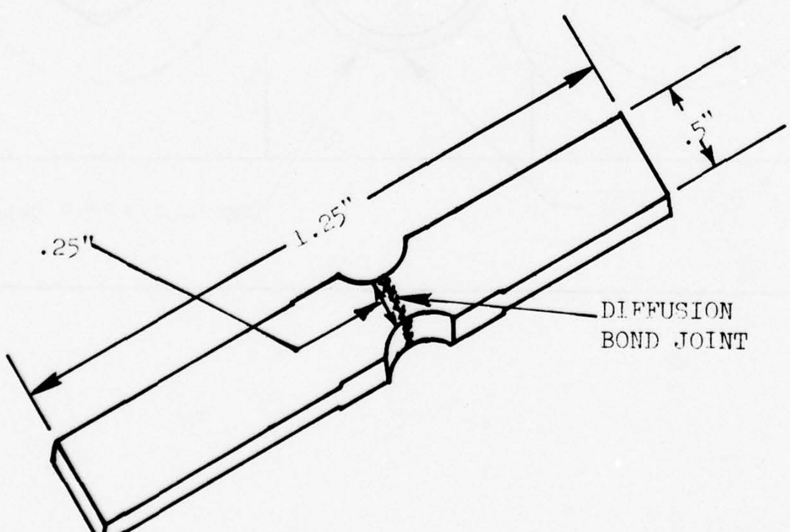


FIGURE 17. RESONANT FATIGUE SPECIMEN CONFIGURATION.

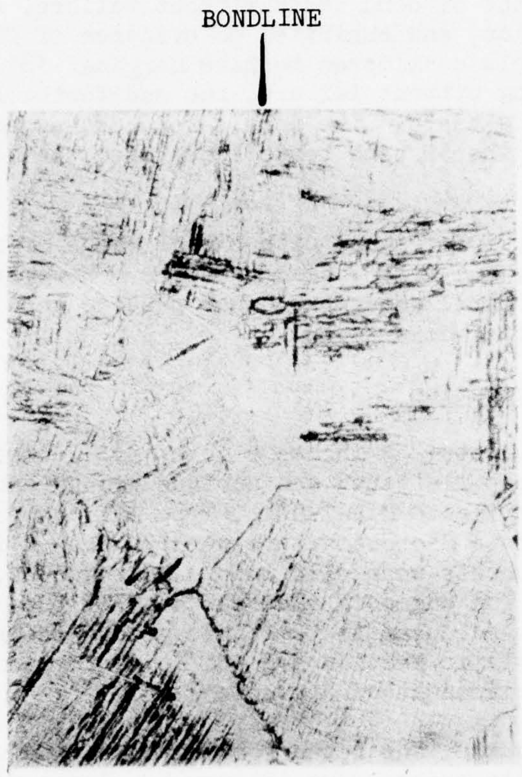


FIGURE 18. MICROSTRUCTURE OF A GOOD QUALITY CSDB JOINT. 200X

4.4 Flat Panel Test Results

The results of the mechanical property testing are provided in Table II. Thirteen panels were evaluated which reflect differences in bonding parameters and geometric variables of the joint. The panels are listed in the table in a general arbitrary order of decreasing joint quality. Panels 1 to 6 are classified to have general acceptable joint quality, panels 7 to 9 are considered marginal, and panels 10 to 13 are regarded unacceptable. The panels classified as having generally acceptable joints withstood the 5T bend tests without failure, exhibited reasonable ductility in tension, and exhibited no evidence of flat fracture in fatigue. The panels considered to have marginal joint quality withstood the 5T bend testing without failure, but manifested regions of flat fracture in tensile tests. The panels regarded as unacceptable generally did not withstand the 5T bend tests and showed the lowest ductility in tension tests.

Good joint quality is produced with a wide range of standard conditions of current, speed, and force, head pressure. However, nonparallel edge fitup, rounded corners, and gaps do not produce good quality joints even under optimum bonding conditions.

4.5 Pre-form Fabrication

Two triple width sheets, 54 inches wide by 316 inches long by 0.145 inch thick, of creep flattened and surface ground annealed Ti-6Al-4V sheet stock conforming to MIL-T-9046, Type III, composition "C" with fine grain alpha-beta microstructure were purchased for this program. The triple width sheets were slit into single widths, 16.364 inches by 139 inches long. The edges or side surfaces of the single width sheet were machined perpendicular to the flat, ground thickness surface as described previously in Section 3.1 and in conformance to the final specification requirements of Appendix A.

As reported previously, the brake forming operation was accomplished on a 1000 ton hydraulic brake press, Figure 5. Brake forming process controls were established by undertaking a risk reduction effort using aluminum sheet material and applying the technology to the fabrication of titanium pre-forms. The risk reduction effort included brake forming sections of 7075 aluminum alloy in the T-6 condition for preliminary evaluation. The risk reduction effort was undertaken with a high degree of confidence because 7075-T6 aluminum sheet material has the same general spring-back characteristics as the titanium 6Al-4V alloy. Other contributing factors leading to the use of 7075-T6 aluminum sheet as a risk reduction effort was the significantly lower cost of the aluminum sheet as compared to titanium 6Al-4V sheet and the ready availability of the aluminum sheet.

FLAT PANEL NUMBERS	VI		I	II		VII	
SAMPLE NUMBERS	1	2	3	4		5	6
Bonding Parameters							
Current, Amps	10,400	10,100	10,500	11,100		10,767	11,4
Speed, In./Min	3.18	4.3	3.75	3.75		3.75	3.
Force, Lbs (Head)	2600	2600	2600	2600		2600	26
Fit-up Variables	Std	Std	Std	Offset with 0.005-0.010 In. Shim		Std	S
5T Bend Tests - Top Down	5T, 5T	5T, 5T	5T, 5T 5T, 5T	5T, 5T		5T	5
Tensile Tests							
0.2% Yield, Ksi	133.5	137.3	133.6	136.0	137.2	135.2	136.
Ultimate Tensile Strength, Ksi	146.0	147.5	148.6	149.8	150.8	150.8	150.
1% Elongation	14.9	13.4	12.4	11.4	10.9	6.5	6.
Location of Failure	HAZ	HAZ	HAZ	JZ	HAZ	PM	* P
Resonant Fatigue Tests							
Cycles to Failure at 0.100 In. Deflection	$2x10^5$	$1.2x10^5$	$7.1x10^4$	$1.2x10^6$	$1.6x10^5$	$1x10^5$	1.4x10
Location of Failure	PM FE	JZ	JZ	JZ	JZ	JZ	J

* 0.001 In. Deflection

5T - Withstood 5T bend test without failure.

PM - Failure occurred in parent metal away from joint and heat affected zone.

HAZ - Parent metal type failure in heat affected zone, i.e., grain pullout on both sides plus ductility.

JZ - Parent metal type failure at joint region, i.e., grain pullout on both sides of joint plus ductility.

FF - Failure occurred at original bond line with no grain pullout and limited or no ductility (flat fracture).

FE - Failure initiated on edge of reinforcement foil.

TABLE II

IG CONDITIONS ON MECHANICAL PROPERTIES

	VIII		V				IV		V		III	
	7		8		9		10		11		12	13
433	11,106		10,500		10,500		10,500		10,500		11,100	11,100
.75	3.75		3.75		3.75		3.75		3.75		3.75	3.75
600	2800		2600		2600		2600		2600		2600	2600
Std	Std		Insert with 0.001 In. Ti Foil		Insert with 0.002 In. Ti Foil		Round Corner 0.010 In. Radius		Insert with 0.003 In. Ti Foil		0.005" Notch Top Side	0.005 In. Notch Bottom Side
5T	5T		5T		5T		JZ		5T, 5T, FF		FF, 5T	FF,5T
6.3	138.3	136.7	135.0	136.0	130.0	134.6	134.6	135.8	134.4	137.3	138.5	139.9
.6	148.6	150.1	147.9	148.1	146.6	149.8	147.8	146.5	150.8	149.2	150.7	149.9
6.5	9.5	5.5	6.8	4.5	6.8	7.5	7.5	5.0	11.4	10	4.2	2.7
PM	JZ	80%JZ 20%FF	PM FE	50%JZ 50%FF	70%JZ 30%FF	70%JZ 30%FF	JZ	JZ	HAZ	HAZ	HAZ	90%JZ 10%FF
10^5	$2x10^6$	$2.4x10^5$	*6.7×10^4	6.9×10^4	$1.2x10^5$	$1.9x10^4$	1.3×10^4	$2.5x10^4$	6.7×10^4	4.3×10^4	$4.4x10^5$	$3.5x10^5$
JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ

TA

EFFECT OF VARIOUS BONDING C

FLAT PANEL NUMBERS	VI		I	II		VII	
SAMPLE NUMBERS	1	2	3	4		5	6
Bonding Parameters							
Current, Amps	10,400	10,100	10,500	11,100		10,767	11,433
Speed, In./Min	3.18	4.3	3.75	3.75		3.75	3.75
Force, Lbs (Head)	2600	2600	2600	2600		2600	2600
Fit-up Variables	Std	Std	Std	Offset with 0.005-0.010 In. Shim		Std	Std
5T Bend Tests - Top Down	5T, 5T	5T, 5T	5T, 5T 5T, 5T	5T, 5T		5T	5T
Tensile Tests							
0.2% Yield, Ksi	133.5	137.3	133.6	136.0	137.2	135.2	136.3
Ultimate Tensile Strength, Ksi	146.0	147.5	148.6	149.8	150.8	150.8	150.6
1% Elongation	14.9	13.4	12.4	11.4	10.9	6.5	6.5
Location of Failure	HAZ	HAZ	HAZ	JZ	HAZ	PM	PM
Resonant Fatigue Tests							
Cycles to Failure at 0.100 In. Deflection	$2x10^5$	$1.2x10^5$	$7.1x10^4$	$1.2x10^6$	$1.6x10^5$	$1x10^5$	$1.4x10^5$
Location of Failure	PM FE	JZ	JZ	JZ	JZ	JZ	JZ
* 0.001 In. Deflection							

5T - Withstood 5T bend test without failure.

PM - Failure occurred in parent metal away from joint and heat affected zone.

HAZ - Parent metal type failure in heat affected zone, i.e., grain pullout on both sides plus ductility.

JZ - Parent metal type failure at joint region, i.e., grain pullout on both sides of joint plus ductility.

FF - Failure occurred at original bond line with no grain pullout and limited or no ductility (flat fracture).

FE - Failure initiated on edge of reinforcement foil.

BLE II

CONDITIONS ON MECHANICAL PROPERTIES

	VIII		V				IV		V		III	
	7		8		9		10		11		12	13
3	11,106		10,500		10,500		10,500		10,500		11,100	11,100
5	3.75		3.75		3.75		3.75		3.75		3.75	3.75
0	2800		2600		2600		2600		2600		2600	2600
a	Std		Insert with 0.001 In. Ti Foil		Insert with 0.002 In. Ti Foil		Round Corner 0.010 In. Radius		Insert with 0.003 In. Ti Foil		0.005" Notch Top Side	0.005 In. Notch Bottom Side
T	5T		5T		5T		JZ		5T, 5T, FF		FF, 5T	FF,5T
3	138.3	136.7	135.0	136.0	130.0	134.6	134.6	135.8	134.4	137.3	138.5	139.9
6	148.6	150.1	147.9	148.1	146.6	149.8	147.8	146.5	150.8	149.2	150.7	149.9
5	9.5	5.5	6.8	4.5	6.8	7.5	7.5	5.0	11.4	10	4.2	2.7
4	JZ	80%JZ 20%FF	PM FE	50%JZ 50%FF	70%JZ 30%FF	70%JZ 30%FF	JZ	JZ	HAZ	HAZ	HAZ	90%JZ 10%FF
5	$2x10^6$	$2.4x10^5$	*$6.7 x 10^4$	$6.9 x 10^4$	$1.2x10^5$	$1.9x10^4$	$1.3 x 10^4$	$2.5x10^4$	$6.7 x 10^4$	$4.3 x 10^4$	$4.4x10^5$	$3.5x10^5$
2	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ	JZ

Initially two-foot long segments of 7075-T6 aluminum alloy were used to establish a technique for brake forming the sheet material to the desired configuration. After successful completion of this task, the brake forming technique was applied to four foot long aluminum segments. Upon successful completion of the effort on the aluminum sheet material, the established technique was applied to brake forming relatively small sections of Ti-6Al-4V sheet material before brake forming the one, six foot Ti-6Al-4V pre-form which was used for the creep forming evaluation, Reference Section 3.2, and two 139 inch pre-forms, S/N 1 and S/N 2 which were used in the initial CSDB attempts. Modifications to the brake forming technique were incorporated in pre-forms S/N 3 through S/N 8 to make them symmetrical, Reference Section 3.3. The modifications to the technique involved brake forming the one inch flat width of the free edges of the pre-form to a greater angle and forming the titanium sheet material in such a manner that the free edges of the pre-form were relatively equally distant from the centerline normal to the flat on the base of the pre-form. The results of this modification was depicted in the pre-form configuration in both the unclamped and clamped condition, Reference Figure 4. The greater angle produced the initial brake forming of the one inch flat width of the free edges and the technique used to obtain a symmetrical pre-form configurations results in the internal height of the pre-form being reduced. Dimensional check of the internal height of the pre-form in the clamped condition disclosed them to be slightly under the dimension established for the pre-forms previously fabricated, pre-forms S/N 1 and S/N 2.

After brake forming, each of the pre-forms was chemically cleaned in nitric-hydrofluoric acid using the general cleaning procedure described in Appendix B. Upon completion of the cleaning operation, the vinyl channeling material was replaced along each 139 inch edge of each pre-form in order to protect the square, sharp, machined edges, as described previously in Section 3.1. Figure 19 illustrates the basic stages of the brake forming sequence and depicts the vinyl material along the free edges of the pre-form. The detailed brake forming operation is described in the actual Operation Sheets, Section 10.3, Appendix C. The cleaned pre-forms with the vinyl protective strips installed were wrapped in aluminum backed paper, packaged in wooden crates, and shipped to the subcontractor for bonding. A total of eight pre-forms were shipped to Solar for bonding.

The CSDB process was performed by Solar using the same prebonding preparation employed for the flat panels as described in Section 4.1. As stated previously, final modification to both the pre-form configuration and the bonding tool was not accomplished until after actual hardware had been fabricated and trial bonding attempts have been performed. The first five pre-forms, S/N 1 through 5 were involved in modification and trade-off between the pre-form shape and tooling design. The remaining three pre-forms, S/N through 8 were diffusion bonded in accordance with the techniques and procedures established from the trade-off. A detail

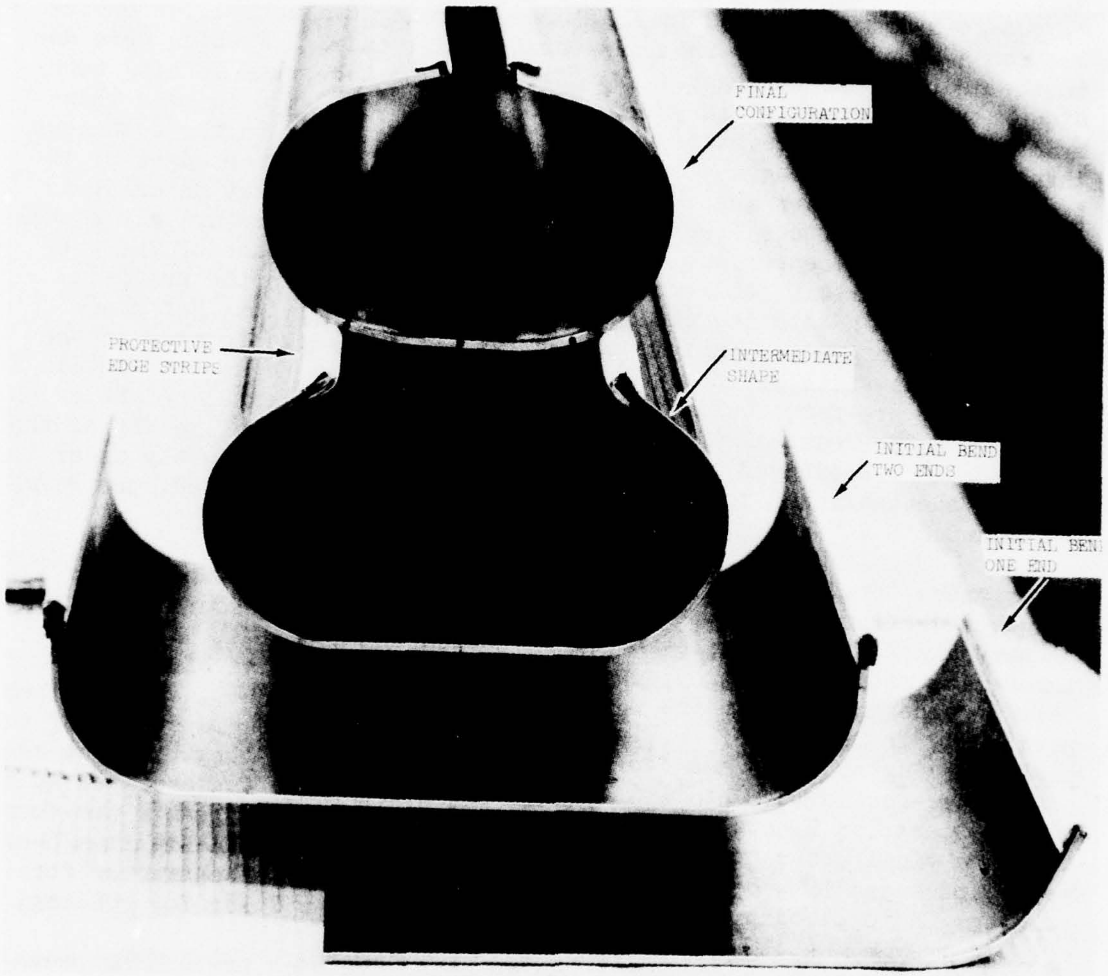


FIGURE 19. BASIC STAGES OF BRAKE FORMING SEQUENCE FOR ELLIPTICAL CONFIGURATION.

description of the events and circumstances involving each of the pre-form, S/N 1 through 5 and how these conditions and situations influenced the modification and trade-off is provided in the following subsections, 4.5.1 to 4.5.5. Prior to bonding, each of the pre-forms was cleaned in nitric-hydrofluoric acid for at least two minutes and rinsed in clean water.

4.5.1 Pre-form - Tube Spar S/N 1

Prior to brake forming, the edges along the longitudinal length of the first titanium sheet stock material machined for this program were noted to have been unintentionally deburred. It should be recalled that square, sharp, knife edges are required for good quality diffusion bonds. Remachining of the edges to within specification minimum width requirements of 16.354 inches was unsuccessful in completely removing the chamfer produced by the deburring. The full size, 139 inch long by 16.364 ± .010 inches wide by .145 ± .005 inches thick titanium sheet material was brake formed to the initial pre-form elliptical shape in order to demonstrate that the brake forming procedure established on the aluminum material could be successfully accomplished on titanium sheet in the full size length. Upon successfully cold brake forming, the titanium sheet material pre-form was shipped to Solar for use to proof test the bonding tool fixture, and to establish loading and clamping techniques. Once the tooling was considered adequate, and the loading and clamping technique were regarded satisfactory (later it was determined that both the tooling, and loading and clamping techniques were not adequate) bonding of the pre-form was performed to demonstrate that bonding could be accomplished on the tooling fixture. Bend tests and other evaluations relating to the quality of the bonded joint were not conducted on this pre-form because the quality of the bond was known to be questionable due to the rounded edges of the pre-form as cited previously. It was later detected that the internal mandrel had been tilted during the bonding operation of this pre-form. Details of the tilting condition of the internal mandrel will be described in subsection 4.5.2.

4.5.2 Pre-form - Tube Spar S/N 2

The machined edges of the titanium sheet material for the second and subsequent pre-forms were not deburred and were acceptable for CSDB. The second titanium sheet was cold brake form into the initial elliptical shape, pre-form S/N 2 and forwarded to Solar for CSDB. Loading pre-form S/N 2 into the bonding tool fixture or module presented difficulty as related to seating the free edges of the pre-form onto the internal mandrel and the excessive side force required to close the pre-form. The free edges of the pre-form is defined as the one inch horizontal flat area that contacts the wheel electrode on the external surfaces and the mandrel electrode on the internal surface. Pre-form S/N 2 was loaded into the tooling fixture as well as could be achieved and bonding was attempted.

The fitup condition of the pre-form in the tooling module was considered to be adequate at the time of bonding Upon removal of the pre-form tube from the tooling fixture after being subjected to the CSDB process, the joint at one end of the pre-form ruptured, zippered open for approximately one third of its longitudinal length, approximately three feet. Subsequent examination revealed that the joint interfaces exhibited evidence of machining marks. These machining marks indicate that the butted interface or edges were not in intimate contact during the diffusion bond process or that no diffusion action took place. Macro-examination of the cross sectional segment, removed from the midsection of the pre-form, illustrates that the butted edges were actually in intimate contact, but were not joined by diffusion bonding, Reference Figures 20 and 21. Macro-examination also disclosed the heat affected zone, produced by the diffusion process, was not what is typically experienced with adequate diffusion bonded joints especially as observed on the internal area. The pattern of the heat effected zone was not symmetrical and the joint location was not in the center of the heat effected zone. Patterns of the heat effected zone from the subject pre-form and from an adequately diffusion bonded joint are depicted in Figures 20 and 22. The joint location on the internal area of the pre-form was observed to be 1/8 inch from the heat effected zone at one end and 1/2 inch from the heat effected zone at the other end, Reference Figure 20. Micro-examination clearly depicts the lack of diffusion at the joint interface, Reference Figure 23. Visual examination of the internal area of the pre-form revealed that the mandrel had not made complete contact with the pre-form across the one inch flat region. Only 5/8 inch contact area was observed on the internal area of the pre-form. The contact area was directly related to the size and shape of the heat effected zone discussed previously in the macro-examination and illustrated in Figure 20. The lack of internal contact surface strongly indicated that the mandrel had been tilted during the bonding operation and was directly related to the cause of the poor bond quality. It was at this point in time that pre-form tube S/N 1 was checked and found to exhibit the same condition as related to the tilting of the internal mandrel.

Modifications to the mandrel were incorporated at this time in order to eliminate recurrence of this situation. The modifications included included increasing the radius at the top corners of the mandrel in an effort to prevent any hang-up of the free edges of the pre-form and to install additional and larger centering devices along the longitudinal length of the mandrel to prevent tilting of the mandrel.

In addition to the tilted mandrel condition, another situation existed that significantly contributed to the lack of bonding of pre-form S/N 2. The loading and clamping technique employed during assembly of the pre-form into the bonding tool fixture is critical and requires some skill. The side and top clamping pressure must be applied gradually and alternately in order that the interface or butted edges to be joined

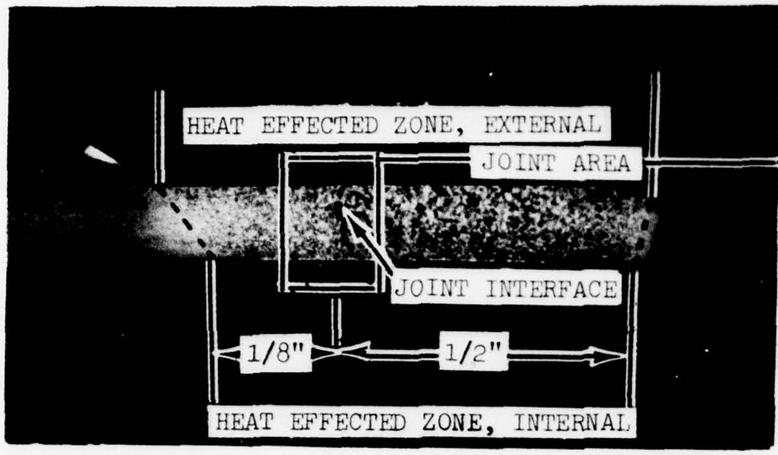


FIGURE 20. PHOTOMACROGRAPH OF CROSS SECTION OF PRE-FORM. S/N 2, MAG. 3X.

NOTE: UNSYMMETRICAL PATTERN OF HEAT EFFECTED ZONE & LOCATION OF JOINT INTERFACE AS RELATED TO HEAT EFFECTED ZONE.

FIGURE 21. PHOTOMACROGRAPH OF C JOINT AREA. MAG. 10

NOTE: ARROW DENOTES BUTTED EDGES RATHER THAN JOINED BY DIFF

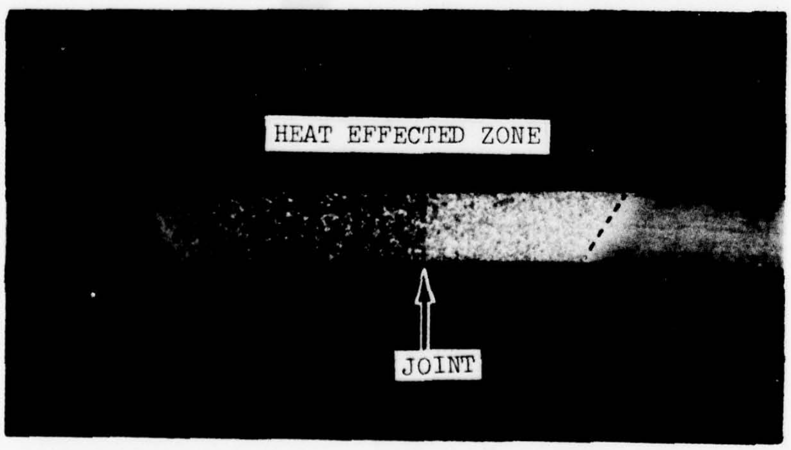
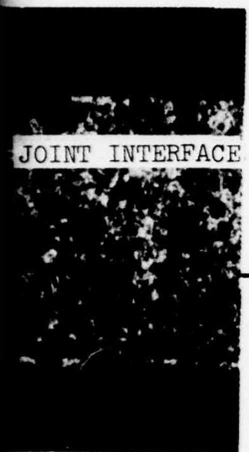


FIGURE 22. PHOTOMACROGRAPH OF CROSS SECTION OF A TYPICAL CSDB JOINT. MAG. 3X

NOTE: HEAT EFFECTED ZONE PATTERN AND LOCATION OF JOINT.



' CROSS SECTION AT
10X.

GES IN INTIMATE CONTACT
IFFUSION BONDING.

FIGURE 23. **PHOTOMICROGRAPH OF CROSS SECTION OF PRE-FORM S/N 2**
CLEARLY DEPICTING LACK OF DIFFUSION AT JOINT INTERFACE.
MAG. 50X.

2

are in intimate contact, with no edge gapping, and aligned along the longitudinal dimension of the pre-form. Proficiency in the loading and clamping technique is contingent upon experience rather than analytical interpretation.

A second contributing factor in the lack of bonding of pre-form S/N 2 was the nonsymmetrical configuration of the pre-form about its vertical center and to the parallelism of the top and bottom flat surfaces. The centerline at the base of the pre-form did not coincide with the bondline or projected bondline at the top of the pre-form and consequently more pressure was applied to one side of the bonding tool fixture. The additional pressure was required in order to close the pre-form to the proper center position for bonding inside the bonding tool module. This side pressure contributed to the tilting of the mandrel. Since the internal mandrel was tilted, the joint over the flat area could not be brought down parallel with the bottom and seated firmly against the mandrel.

Modifications to the pre-form were incorporated at this time in order to provide a more satisfactory pre-form. These modifications included a tighter or smaller bend radius at the upper quadrant of the pre-form, brake forming the sheet material to produce a relatively symmetrical pre-form, i.e., the centerline at the base of the pre-form will coincide with the bondline or projected bondline at the top of the pre-form and minimizing or reducing the gap of the pre-form between the edges to be bonded in the unclamped condition. The tighter or smaller bend radius will produce relatively parallel top and bottom flats when the pre-form is clamped with only side pressure. This parallel condition will require little force to seat the free edges or top flats onto the internal mandrel using the top hold down clamps. A symmetrical pre-form will require generally equal side pressure to close the pre-form, therefore reducing the chances of tilting the mandrel. Minimizing or reducing the gap of the unclamped pre-form will also reduce the side pressure required to close the pre-form to the desired clamped position. All three of these modifications will assist in the assembly of the pre-form in the bonding tool fixture and will contribute to producing a better end product.

4.5.3 Pre-form - Tube Spar S/N 3

Pre-form S/N 3 and subsequent, S/N 4, S/N 5, S/N 6, S/N 7, and S/N 8, were brake formed symmetrically in accordance with the procedure described in the Operation Sheets, Appendix C. Because of the technique required to obtain a symmetrical pre-form with parallel top and bottom surfaces, the internal height dimension of the pre-form S/N 3 in the clamped condition was reduced by approximately 1/2 inch from the original internal height dimension used on pre-forms S/N 1 and S/N 2. This reduction in internal height dimension of the pre-form necessitated rework of the mandrel by reducing its overall height. Reduction in the overall height dimension of the mandrel was accomplished by machining 1/2 inch of material along the longitudinal length of the mandrel.

Upon loading the pre-form into the tooling fixture, fitup problems existed again making bonding a very high risk venture. The tooling was not capable of clamping the free edges of the pre-form firmly onto the top of the internal mandrel. Several attempts to seat the free edges along the longitudinal length of the pre-form resulted in a gap of approximately .007 inch between the internal surface of the pre-form along one free longitudinal edge and the top of the mandrel. In an effort to improve the fitup condition and subsequently the odds for a successful bonded pre-form, the one free longitudinal edge of the pre-form was bent along its longitudinal length. Bending of the edge was accomplished by removing the internal mandrel and using the force from the wheel electrode of the CSDB machine, plastically deforming the edge of the pre-form. After bending of the one free longitudinal edge, the fitup condition was improved and bonding was attempted. In addition to deforming the edges, the pre-form was turned end-to-end position in the tooling fixture for bonding.

After the bonding attempt, the pre-form was removed from the tooling fixture. Visual inspection of the pre-form tube showed that it did not rupture or zipper open as the previous pre-form tube, S/N 2. However, a four-to-five-inch length separation emanated from V-notch at one end of the pre-form tube as shown in Figure 24. A full one inch contact area was observed on the titanium foil on both the internal and external areas of the pre-form tube indicating that the internal mandrel had not tilted. The full one inch contact area can also be observed in Figure 24. Subsequent bend tests from each end of the pre-form tube resulted in fracturing of the specimens through the bonded joint. Machining marks were observed on the fracture interfaces indicating lack or loss of side pressure as shown in Figure 25. Macro- and micro-examinations confirm the results of the bend test depicting little or no diffusion in the bond joint with an unsymmetrical pattern of the heat effected zone, similar to the conditions observed for pre-form tube S/N 2, Reference Figures 26 and 27.

An analytical analysis on the contact angle of the upper clamp and the pre-form was performed. The data obtained from this analysis disclosed that the coefficient of friction between the steel and titanium at the angle where the upper clamp contacted pre-form #3 was not sufficient to prevent slip of the pre-form when it was heated and expanded. It was further determined that relocating the contact points of the upper clamp 1/2 inch in the downward direction, toward the horizontal center-line of the pre-form, would prevent slippage of the pre-form on heat up.

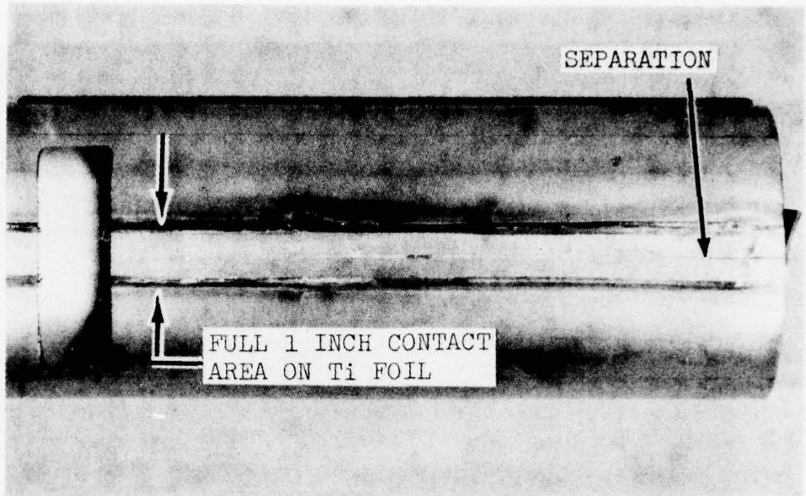


FIGURE 24. PRE-FORM S/N 3 WITH SEPARATION EMANATING FROM ONE END.

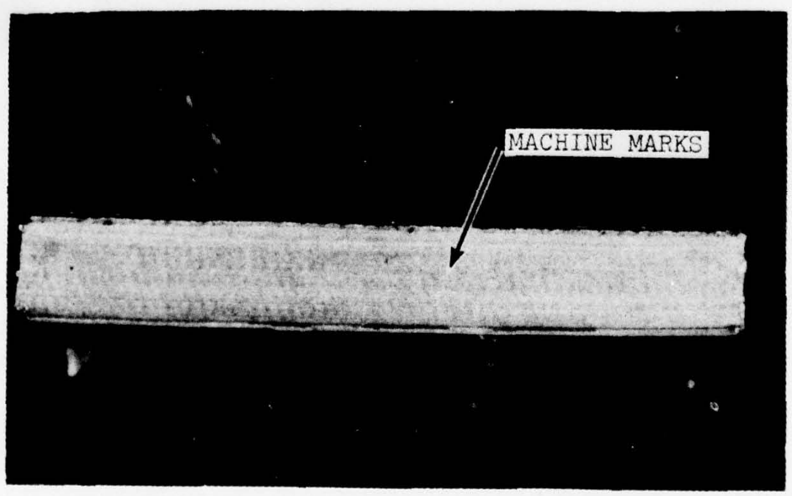


FIGURE 25. FRACTURE SURFACE THROUGH BOND JOINT OF BEND TEST SPECIMEN PRE-FORM S/N 3.

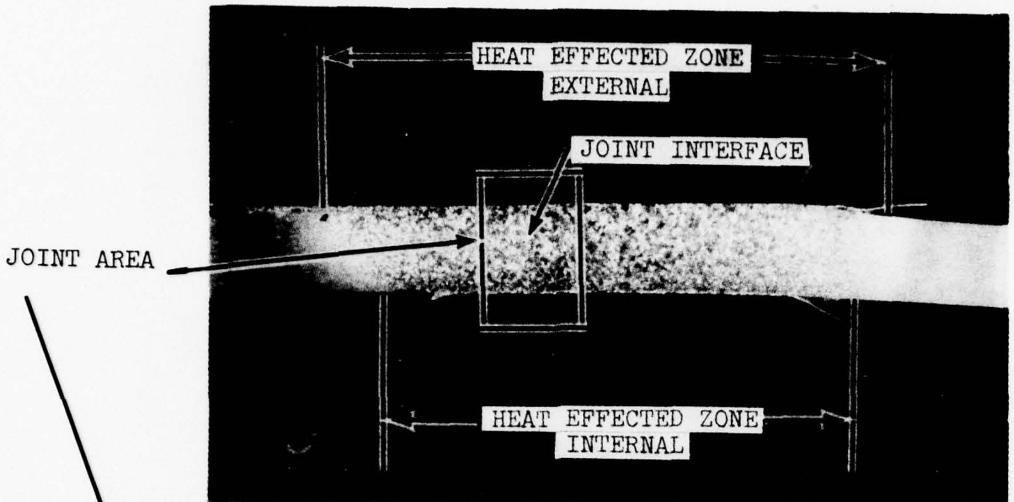


FIGURE 26. **PHOTOMACROGRAPH OF CROSS SECTION OF PRE-FORM S/N 3** AT BOND AREA. NOTE UNSYMMETRICAL PATTERN SIMILAR TO PRE-FORM #2, FIGURE 20. MAG 2X.

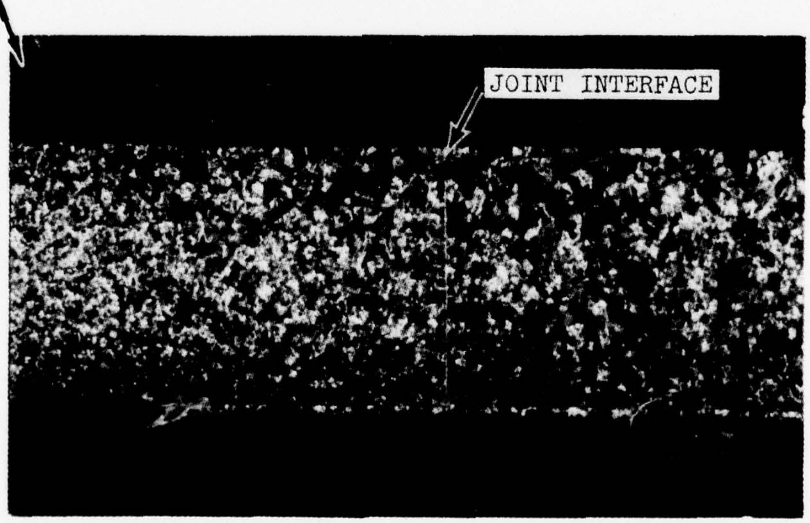


FIGURE 27. PHOTOMACROGRAPH OF CROSS SECTION OF PRE-FORM S/N 3 JOINT AREA. NOTE BUTTED EDGES IN INTIMATE CONTACT RATHER THAN JOINED BY DIFFUSION BONDING. MAG. 10X.

4.5.4 Pre-form - Tube Spar S/N 4

Relocation of the contact points of the upper side clamps to prevent slippage was readily achieved on the existing tooling by adding a 1/2 inch diameter rod beneath and adjacent to the existing 3/4 inch rod along the longitudinal dimension of the tooling fixture as illustrated in Figure 28. This arrangement changed the contact angle of the upper side clamp to a position on the pre-form where the coefficient of friction between the steel side clamp and the titanium pre-form was significantly higher to prevent slip when the pre-form was heated and expands. The initial installation attempts to clamp and fit pre-form S/N 4 into the bonding tool fixture were not satisfactory. Problems consisting of seating the free edges of the pre-form firmly onto the internal mandrel while maintaining the free edges horizontal to the base of the pre-form and maintaining the surfaces to be joined in intimate contact still existed. The problem condition is depicted in Figure 29. Adequate positioning of the pre-form within the tooling fixture is achieved by alternately adjusting the top and side clamps of the fixture in such a manner that the surfaces of the pre-form to be bonded are placed in intimate contact and remain in that condition while the external surface of the free edges are positioned horizontally and are firmly seated onto the internal mandrel. After obtaining an apparent satisfactory clampup and fitup condition as depicted on Figure 30, bonding of pre-form S/N 4 was attempted.

Upon completion of the bonding operation and during removal of the pre-form tube from the tooling fixture, the pre-form tube ruptured, zippering open along the joint area at the start end, for a distance of approximately four feet. Visual inspection disclosed no gross abnormalities that could have caused or contributed to the poor bond condition. Examination of the cross section of a non-ruptured area disclosed a nonsymmetrical heat effected zone which is indicative of poor bond quality and incomplete heating during the bonding cycle, Reference Figure 31. The insufficient heating during the bonding cycle was attributed to poor fitup condition, i.e., the free edges of the pre-form were not seated firmly onto the internal mandrel, resulting in lack of lateral forging pressure. Adequate lateral forging pressure is obtained when the surfaces to be joined are in intimate contact, contained, heated to elevated temperature, and maintained in that situation for a significant period of time. When the external wheel electrode force is applied to the joint area, the poor fitup condition produces a significant difference in the actual force and temperature between the external and internal surfaces of the pre-form at the joint area. A major portion of the force from the wheel electrode is used to seat the internal surfaces of the free edges onto the internal mandrel. The compression force on the external and internal surfaces of the joint area are significantly different and are directly related to limiting heat transfer from the thermal strip to the pre-form. The incomplete heating is illustrated by the difference in grain size of the heat effected zone and the grain size at the end of the foils, Reference Figures 32 and 33. Grain size increases with increase in temperature. On a completely or adequately heated and bonded joint, the heat effected zone would extend symmetrically to both ends of the foils on the external and internal surfaces. No depressions, indentations, or forging flow, which would indicate more than adequate pressure, were observed at the foil edges of pre-form S/N 4. In order to correct the situation, the free edges of the pre-form must be seated firmly onto the internal mandrel prior to bonding, or increase the amount of heat absorbed by the pre-form. Seating the pre-form onto the internal mandrel can be achieved by modifying the fixed height mandrel to a variable height mandrel. Increasing the amount of heat to the pre-form can be achieved by using a more conductive and/or higher melting point thermal strip material, e.g., tantalum.

4.5.4.1 Pre-form - Tube Spar S/N 4A

In an effort to determine the effects of rebonding and the use of tantalum thermal strips, a seven foot non-ruptured segment of the pre-form tube S/N 4 was loaded into the tooling fixture and rebonded. The segment of pre-form was alternately assembled with tantalum and steel thermal strips on both external and internal surfaces in an effort to evaluate all possible combinations of tantalum and steel. Results of the rebond operation indicated that the use of tantalum thermal strips (tantalum thermal strips on the external and internal surfaces) provides the most encouraging approach in obtaining a satisfactory bonded joint. However, some additional basic work would have to be accomplished before bonding of a full size, 139 inch pre-form could be attempted. Additional parametric parameters would have to be determined.

4.5.5 Pre-form - Tube Spar S/N 5

The full size 139 inch pre-form S/N 5 was loaded into the bonding tool fixture without the internal mandrel being installed in order to determine its internal height dimension in the clamped condition. This internal height dimension determined the overall height requirement for the mandrel and was used to establish shim thickness for modification to the fixed height mandrel to a variable height mandrel. Results of this loading effort disclosed that the internal height dimension of pre-form S/N 5 in the clamped condition was 3.752 inches. This dimension is similar to the 3.750 inch internal height observed previously for pre-form S/N 4. Approximately 0.002 inch shim material was required to be added to the mandrel height to achieve an adequate internal height dimension. Pre-form S/N 5 was cut into four equal segments, each approximately 35 inches long. The four segments were used to establish an optimum bonding cycle which was incorporated to bond the full size pre-form S/N 7 and 8. The optimum bonding cycle was established using tantalum material for thermal strips on both the external and internal surfaces of the pre-form.

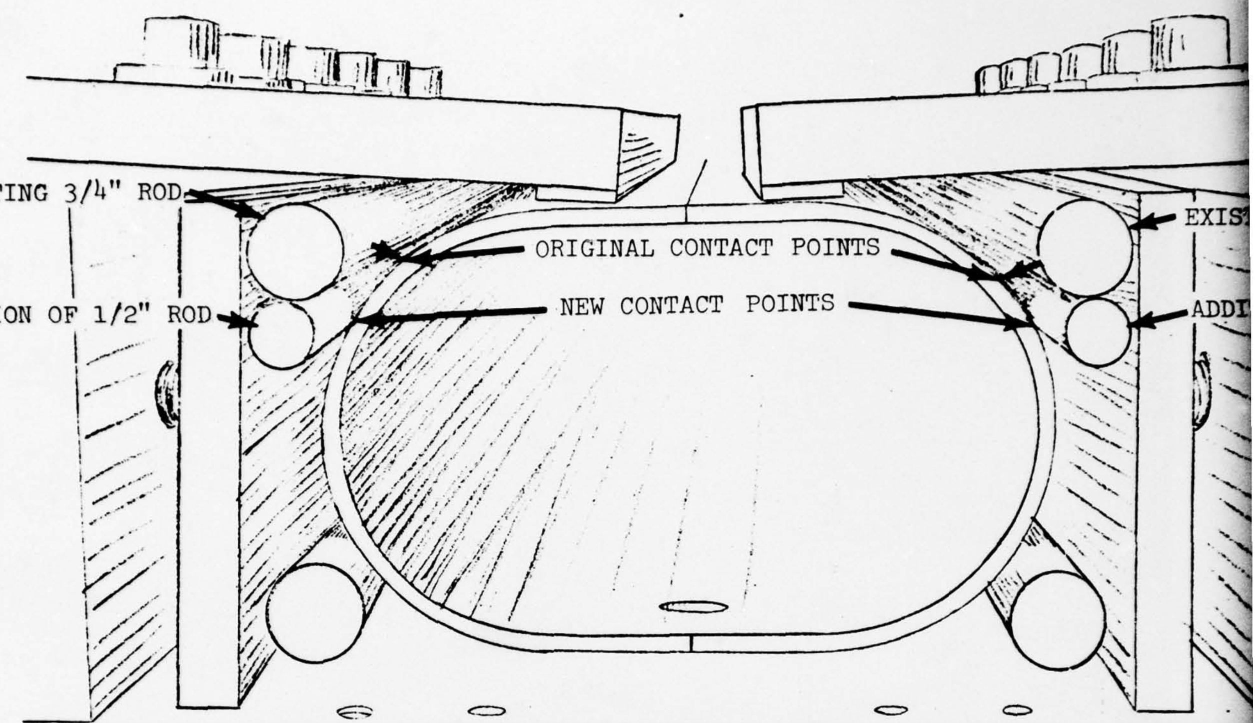


FIGURE 28. SKETCH OF PRE-FORM IN TOOLING, DEPICTING RELOCATION OF CONTEST POINTS BY THE ADDITION OF 1/2 INCH DIAMETER ROD.

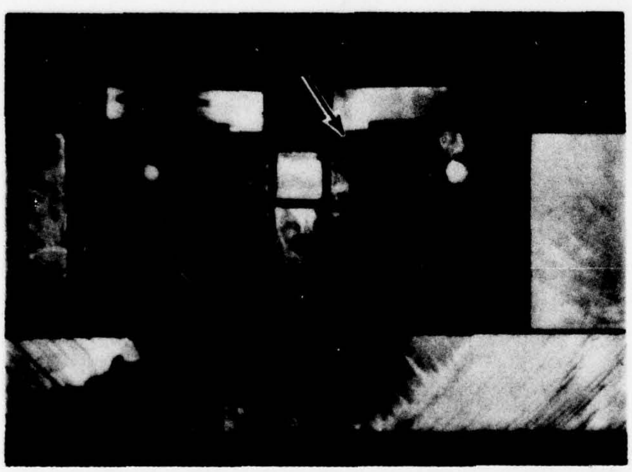


FIGURE 29. PRE-FORM INSTALLED IN TOOLING. ARROW DEPICTS FREE EDGES OF PRE-FORM NOT SEATED FIRMLY ON MANDREL.

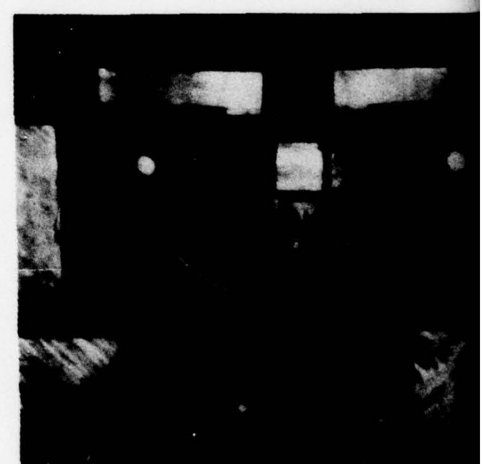
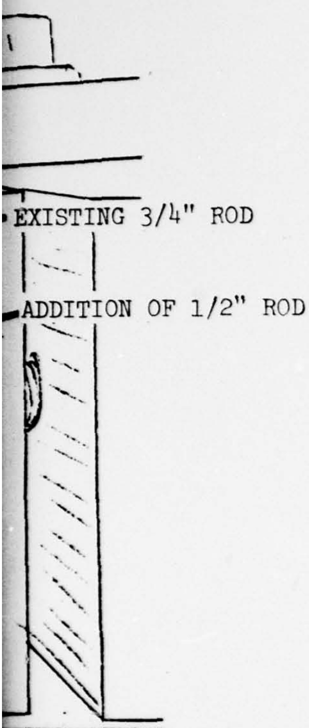
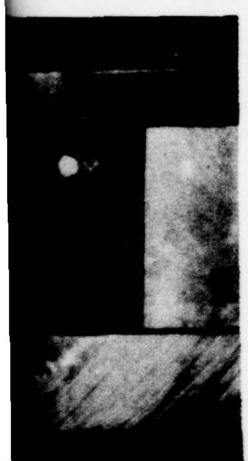


FIGURE 30. PRE-FORM INSTALLED I
APPARENT GOOD CLAMPU
UP CONDITION.





LED IN TOOLING.
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2

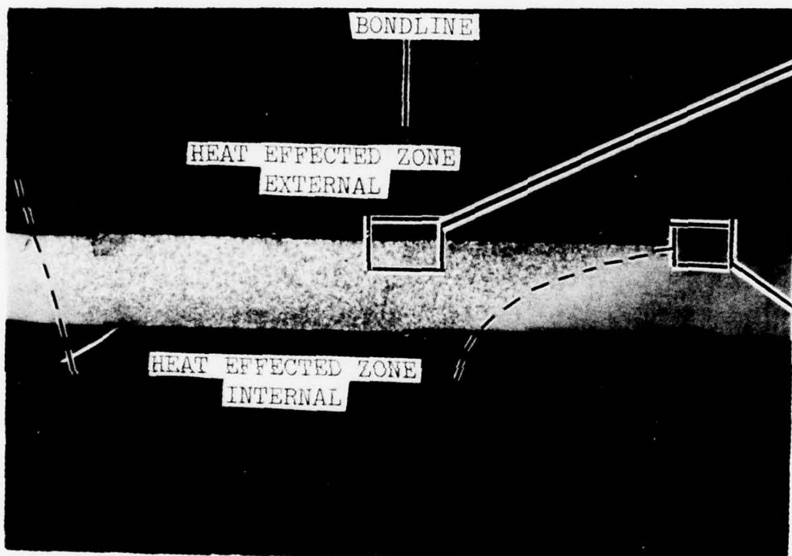


FIGURE 31. CROSS SECTION OF PRE-FORM TUBE S/N 4 DEPICTING NONSYMMETRICAL HEAT EFFECTED ZONE. MAG. 2X.

FIGURE 32. PHOTOMICROGRAPH OF CROSS PRE-FORM S/N 4 AT BOND JC RELATIVELY LARGE GRAIN SI

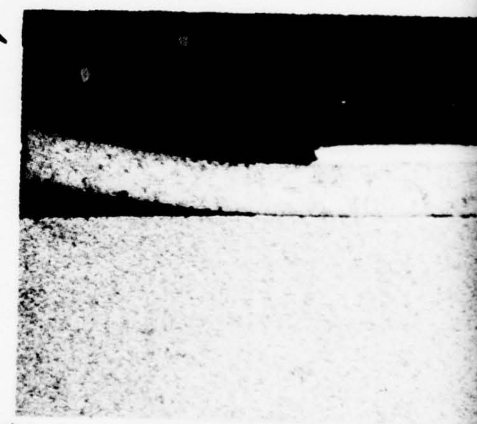


FIGURE 33. PHOTOMICROGRAPH OF CROSS PRE-FORM S/N 4 AT END OF FINE GRAIN SIZE. MAG. 5(

ROSS SECTION OF
D JOINT. NOTE
N SIZE.
MAG. 50X

ROSS SECTION OF
D OF FOIL. NOTE
. 50X

2

4.5.5.1 Pre-form - Tube Spar S/N 5, Segment 1

The first 35 inch segment, with the internal mandrel installed, was loaded into the bonding tool fixture. Some difficulty in obtaining a satisfactory fitup condition of the first segment pre-form S/N 5 was encountered. The difficulty involved the same continuing problem of seating the free edges of the segment pre-form onto the internal mandrel. The situation was resolved by increasing the head pressure of the machine from approximately 2,600 lbs (70 lbs gage pressure) to 2,800 lbs (80 lbs gage pressure), and plastically deforming the free edges of the segment in accordance with techniques established previously with pre-form S/N 3, Reference section 4.5.3. The head pressure of the machine is defined as the amount of force that is applied to the item to be bonded through the external wheel electrode.

The first segment of pre-form S/N 5, having tantalum thermal strips on the exterior and interior surfaces, was exposed to a bonding cycle with varying currents. The current input was 11,200 amps for the first foot of the segment, 10,500 amps for the center foot, and 10,000 amps for the final or remaining foot. A 1.1 inch wide flat face wheel electrode was employed in place of the 3/4 inch wide wheel electrode used on the previous pre-forms (S/N 1 through S/N 4) and the flat panel parametric study. The reason for the use of the one inch wide wheel electrode was related with a more uniform transfer of heat across and through the one inch wide tantalum thermal strip. The increase in head pressure was used during the bonding operation. The bonding speed was changed from 3.75 inch/min to 3.25 inch/min. Table III lists bonding parameters for the four segments of pre-form S/N 5.

TABLE III

BONDING PARAMETERS FOR SEGMENTS OF PRE-FORM S/N 5

SEGMENT	CURRENT (Amps.) 1st Foot	2nd Foot	3rd Foot	SPEED (in/min)	FORCE Head (lbs)	Gage (lbs)
1	11,200	10,500	10,000	3.25	2,800	80
2	10,500	10,500	10,500	3.25	2,800	80
3	10,500	11,000	11,400	3.25	2,800	80
4	10,500	11,000	11,400	3.25	2,600	70

Upon completion of the bonding operation, the first segment was evaluated by bend test and macro-examination. Results of both tests were encouraging. Bend test specimens taken from each of the three areas with varying current fractured away from the joint area or bondline in the heat effected zone. Macro-examination depicts satisfactory heat effected zone, symmetrical in configuration on both exterior and interior surfaces. From the results of this data, it was indicated that a nominal 10,500 amps would be adequate for bonding. Figure 34 is an overall view of the bonded segment after removal of bend test specimen coupons.

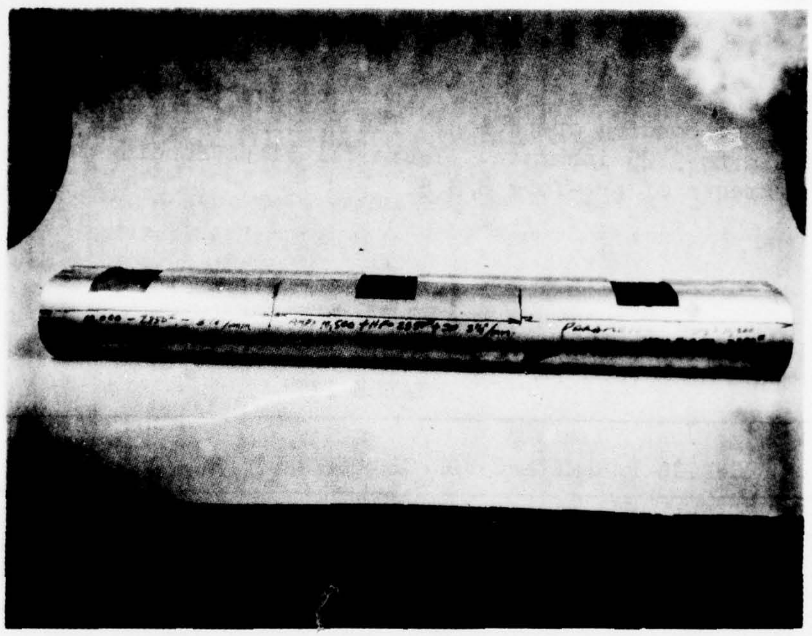


FIGURE 34. PRE-FORM TUBE S/N 5 FIRST SEGMENT. TANTALUM THERMAL STRIPS USED ON EXTERNAL AND INTERNAL SURFACES. WINDOWS IN TUBE DENOTE AREAS WHERE BEND TEST SPECIMENS WERE TAKEN.

4.5.5.2 Pre-form - Tube Spar S/N 5, Segment 2

The second segment of pre-form S/N 5 was bonded using a nominal 10,500 amp current. Bend test and macro-examination showed satisfactory results similar to the results obtained from segment 1. From the data obtained from the second segment, it was decided to evaluate the third segment using a higher current input.

4.5.5.3 Pre-form - Tube Spar S/N 5, Segment 3

The third segment was cleaned for five minutes prior to bonding. This additional cleaning or etching time was an attempt to insure clean, noncontaminated surfaces for bonding. The third segment was bonded using tantalum thermal strips at 10,500 amps for the first foot of the segment (10,500 amps was used as a baseline position), 11,000 amps for the center foot, and 11,400 amps for the final or remaining foot (11,400 amps is close to maximum capability of the machine). Bend test and macro-examination were excellent. Bend test specimens fractured away from the joint area or bondline in the heat effected zone. Subsequent efforts which forced fracture at the bond joint, revealed fracture interfaces of excellent quality. Macro-examination depicted excellent heat effected zone, symmetrical in configuration on both exterior and interior surfaces. Although excellent bonding and symmetrical heat effected zone were obtained, an undesirable condition existed at the edge of the heat effected zone. This undesirable condition manifested itself as nodules of flowed metal resulting from excess forging action. The nodules of flowed metal does not contribute to poor bond quality and in a trade-off of parametric variables, it appears that this condition is controllable. Figure 35 is a cross section of each of the three current conditions used in segment 3 and depicts the excellent symmetrical heat effected zones and the flowed metal condition.

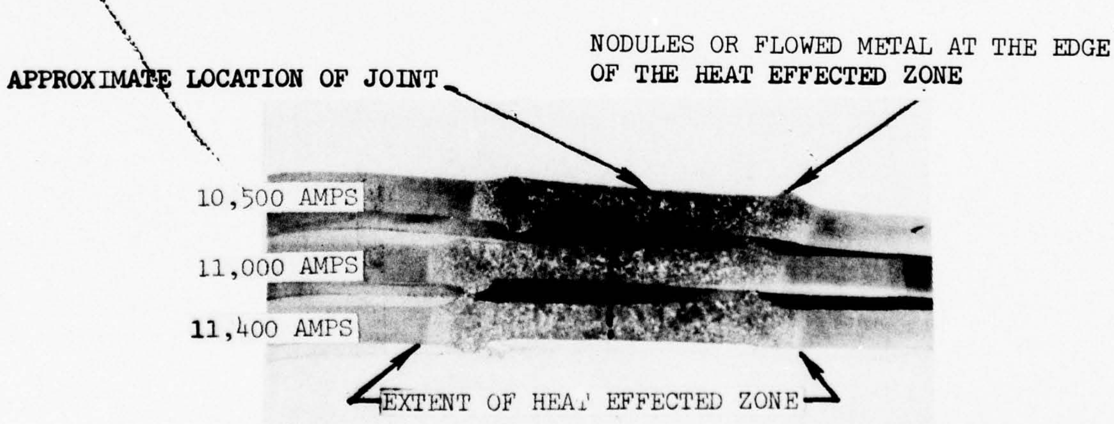


FIGURE 35. CROSS SECTIONS OF SEGMENT 3 OF PRE-FORM S/N 5 DEPICTING EXCELLENT SYMMETRICAL HEAT EFFECTED ZONES AND FLOWED METAL METAL CONDITION. MAG. 1.5X.

4.5.5.4 Pre-form - Tube Spar S/N 5, Segment 4

The fourth and final 35 inch segment from pre-form S/N 5 was bonded using the same parameters and cleaning procedures as employed on the third segment except for the addition of a radius on the longitudinal edges of the thermal strips and reducing the head pressure. The radius was accomplished by sanding the edge of the faying surface into a chamfer. The head pressure was reduced from 2,800 lbs to 2,600 lbs. The reworking of the tantalum and reduction in head pressure was an attempt to minimize the metal flow condition experienced with the third segment. Examination of the bonded tube indicated that the metal flow condition still existed only to a slightly lesser degree. Subsequent bend test and macro-examination were of the same excellent quality as experienced previously with the third segment.

5.0 FABRICATION AND EVALUATION OF CSDB TITANIUM SPAR TUBES

Following completion of the process variable study on flat sheet and based on the results obtained from the four segments of pre-form S/N 5, parameters for bonding the remaining three pre-forms, S/N 6,7, and 8, were selected and the pre-forms were successfully diffusion bonded. Figure 36 depicts the three successfully fabricated spar tubes. The selected parameters were a current input of 11,000 amps, a bonding speed of 3.25 inches per minute, a gage head pressure of 80 lbs which is equivalent to a head pressure of 2,800 lbs, and includes the use of tantalum thermal strips on the external and internal surfaces, a 1.1 inch wide by 12 inch diameter, flat face external wheel electrode, and an increase in cleaning time of the pre-form prior to bonding. Evaluation of the diffusion bonded spar tubes encompassed bend tests, and macro and micro-analysis. Results of these evaluations indicate diffusion bonds of adequate quality. Subsequent sanding and cleaning were performed on the spar tube prior to non-destructive inspection.

5.1 Pre-form - Tube Spar S/N 6

Actual bonding of pre-form S/N 6 was accomplished successfully using the selected parameters and techniques cited in paragraph 5.0 Bend test results were of the same excellent high quality as observed for the third and fourth segments of pre-form tube S/N 5. Visual examination of pre-form tube S/N 6 showed a bonded unit with good forging action at the joint area and an overall satisfactory appearance, Reference Figure 37. The metal flow condition can be observed in Figure 37 and is more dramatically illustrated in a cross sectional view, Figure 38. The cross sectional view also clearly depicts full contact across the internal area of the pre-form joint with the mandrel and a symmetrical heat effected zone extending beyond the width of the thermal strip. An abnormal linear condition was observed along a six inch length on the external surface of the tube as depicted in Figure 39. Evaluation of this linear condition indicated an interaction of the hot metal flow titanium with the mild steel top hold down plates resulting in an unacceptable iron-titanium eutectic alloy. An additional localized interaction condition was observed on the flat area adjacent to the metal flow area and the bond joint as shown in Figure 40. This localized interaction condition, approximately one half to three quarters inches in area, was observed on the external flat section of the spar tube. This localized interaction condition was different in appearance from the linear interaction condition cited previously. The localized interaction condition was flat, exhibiting no pitting or nodules, and manifested cracking within the area of the defect. The cracking appeared to be the result of metal shrinkage induced by metaling and resolidification of localized areas. The melting and resolidification strongly suggest that the localized interaction condition also eminated from contact of hot titanium with steel, possibly the external wheel electrode contacting the titanium pre-form and or titanium foil at a defective weld joint of the tantalum thermal strip. Six, two foot lengths of tantalum strips are

FIGURE 36. THREE, TEN FOOT SPAR TUBES SUCCESSFULLY FABRICATED.

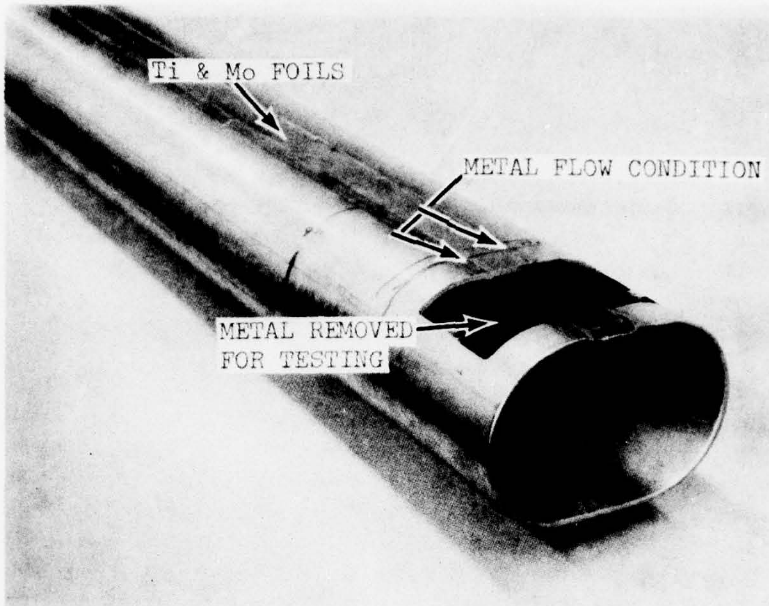


FIGURE 37. VIEW OF PRE-FORM TUBE S/N 6.

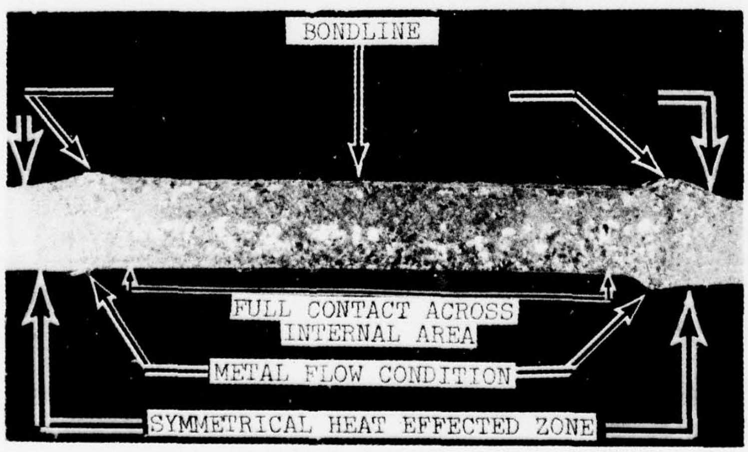


FIGURE 38. CROSS SECTION OF PRE-FORM TUBE S/N 6 ILLUSTRATING FULL CONTACT ACROSS INTERNAL JOINT AREA, METAL FLOW CONDITION, AND SYMMETRICAL HEAT EFFECTED ZONE. MAG. 2X.

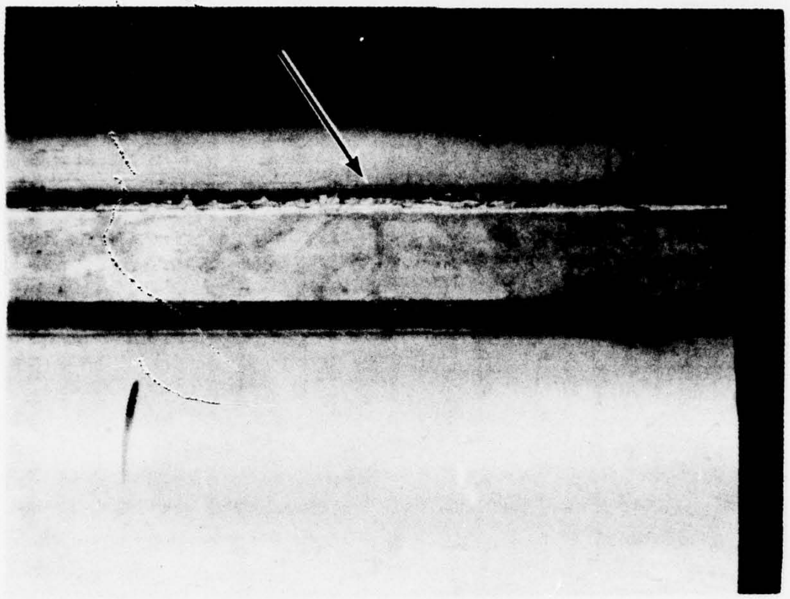


FIGURE 39. LINEAR INTERACTION CONDITION ALONG SIX-INCH LENGTH ON EXTERNAL SURFACE OF PRE-FORM TUBE S/N 6.

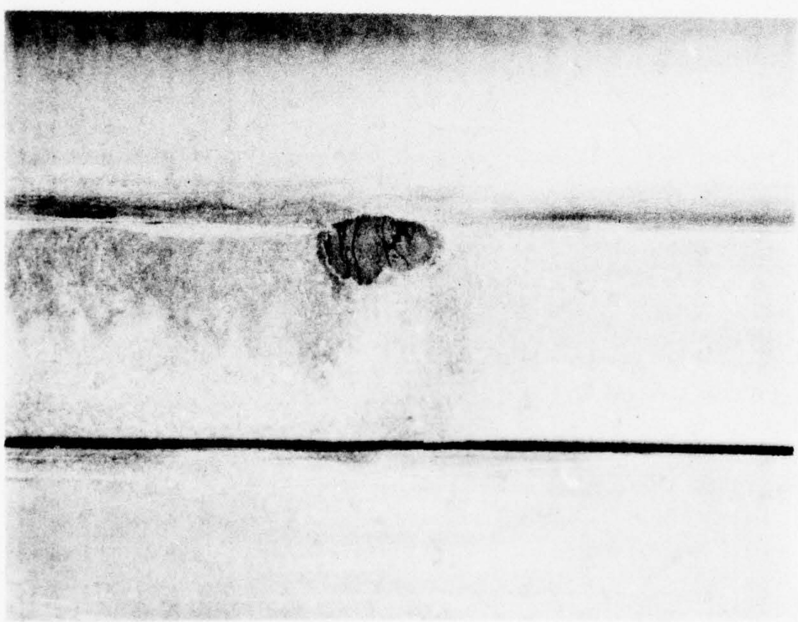


FIGURE 40. LOCALIZED INTERACTION CONDITION ON FLAT AREA ADJACENT TO THE METAL FLOW REGION ON EXTERNAL SURFACE OF PRE-FORM TUBE S/N 6.

welded end to end in order to obtain a twelve foot tantalum thermal strip used in the CSDB Process.

Initial bend testing was performed on pre-form tube S/N 6 in the as bonded condition. Testing was performed by placing a one inch wide by five inch long coupon on a V-block and using a 1 3/4 inch diameter bar to force the coupon down into the V of the block and around the bar until it breaks or bottoms in the V-block. The ratio of the radius of the bar to the thickness of the material was 5.8:1 providing a 5.8T bend test. This 5.8T bend test is considered a severe test. This method of testing anticipated rupture of the coupon at the diffusion bond joint area. The coupon ruptured where expected, as depicted in Figure 41. Examination of the fracture interface disclosed it to be granular in nature with no evidence of flat fractures, Reference Figure 42. Flat fractures at the bond joint are indicative of poor bond quality as illustrated in Figure 43. (Note, Figure 43 is not from pre-form tube 6). In an effort to better define the quality of the bonded joint, coupons were given a full anneal stress relief at 1300°F for one hour and cooled in the furnace with the door opened to 500°F before being removed from the furance and air cooled to room temperature. Subsequent bend test (same method as described previously) resulted in fracture of the coupon at a stress riser, a change in section due to the metal flow condition at the edge of the heat effected zone, half inch from the bonded joint, Reference Figure 44. The force to bend and fracture the stress relieved coupon were at least 35% greater than used to perform the same function on the as bonded coupons. Examination of the fracture interface showed no additional abnormalities other than the change in section due to the metal flow condition that could have contributed to the failure of the coupon. In order to minimize the effect of the change in section due to the metal flow condition, the metal flow condition was blended by grinding and the bend tests were again conducted. One coupon was permanently deformed around the 1 3/4 inch diameter bar without rupturing, Reference Figures 45 and 46, while the other coupon ruptured in the change in section, similar to the previous failure mode, Figure 44. The force to permanently deform the coupon was 100% greater than the force used to rupture the as bonded tube coupon.

Macro- and micro-examination of cross sectional areas of the as bonded preform tube showed a symmetrical heat effected zone extending more than a half inch on either side of the bond joint on both the external and internal surfaces. A comparison of pre-form tube S/N 6 with a cross section of the D-spar described in Section 7 of this report indicates the same general quality, Reference Figures 47 and 48. The forging action of preform tube S/N 6 appears to be of an even higher quality level.

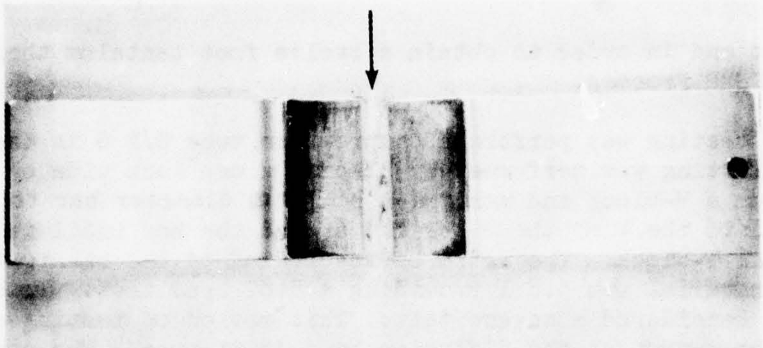


FIGURE 41. BEND TEST COUPON FROM PRE-FORM TUBE S/N 6, FRACTURED AT BOND JOINT AREA AS ANTICIPATED.

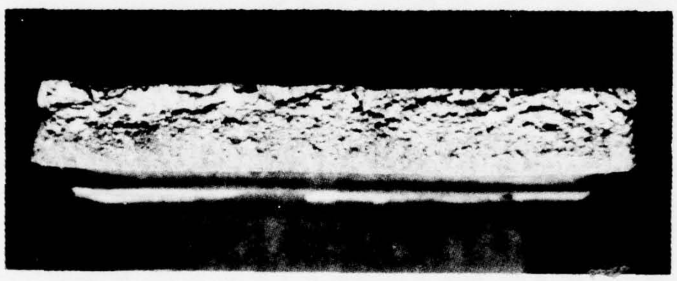


FIGURE 42. FRACTURE INTERFACE OF PRE-FORM TUBE S/N 6 AFTER BONDING CONDITION. MAG. 3X.

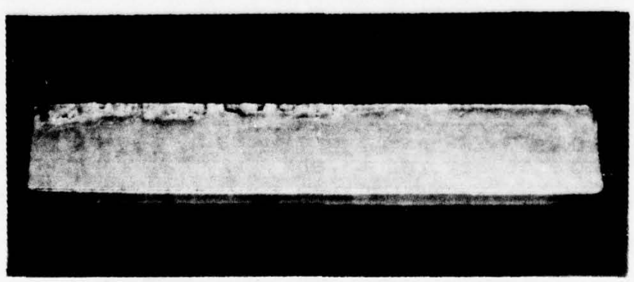


FIGURE 43. TYPICAL FLAT FRACTURE INTERFACE INDICATIVE OF POOR BOND. (NOT FROM PRE-FORM S/N 6).

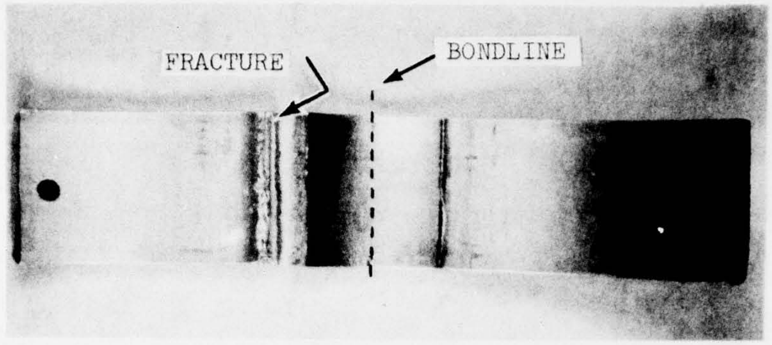


FIGURE 44. **BEND TEST COUPON FROM PRE-FORM S/N 6 AFTER STRESS** RELIEF. ARROW DENOTES FRACTURE AT STRESS RISER, CHANGE IN SECTION DUE TO METAL FLOW.

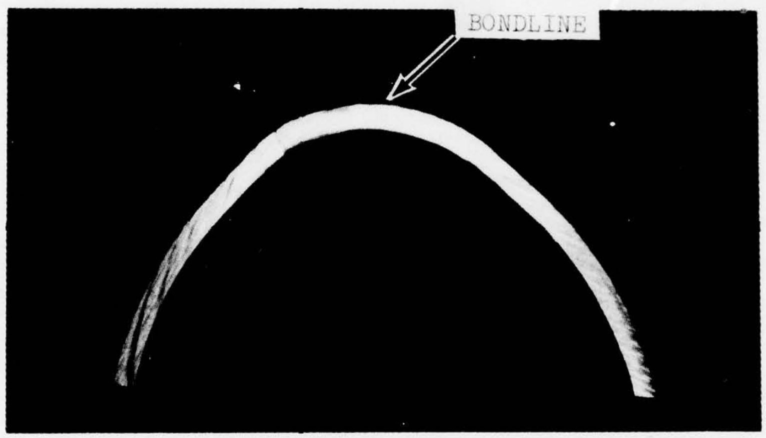


FIGURE 45. **PERMANENTLY DEFORMED COUPON FROM PRE-FORM S/N 6** COUPON HAS BEEN STRESS RELIEVED AND STRESS RISERS BLENDED PRIOR TO 5.8T BEND TEST.

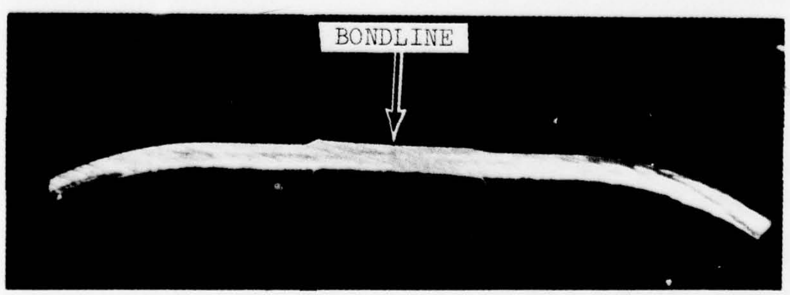


FIGURE 46. **VIEW OF COUPON BEFORE BEND TEST.**

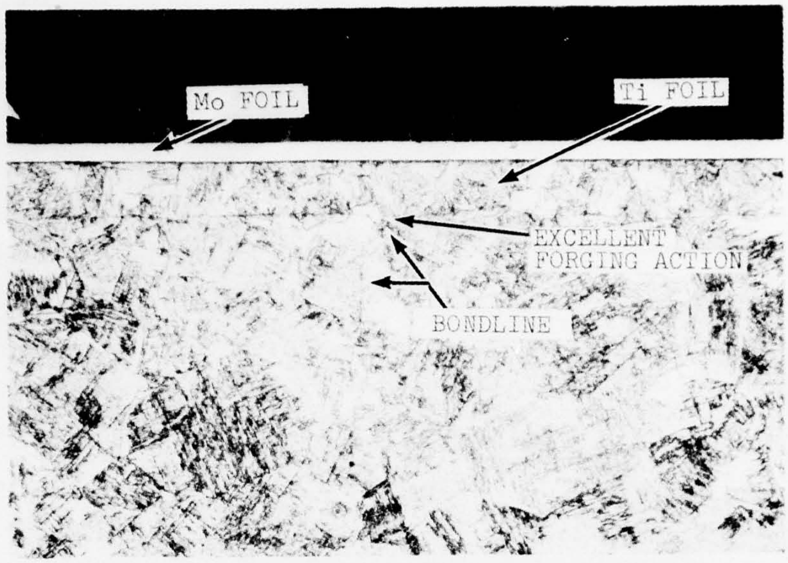


FIGURE 47. CROSS SECTION OF BOND JOINT AREA PRE-FORM TUBE S/N 6. NOTE EXCELLENT FORGING ACTION AT BUTT JOINT AND Ti FOIL JOINT. NO EVIDENCE OF VOIDS. MAG. 50X.

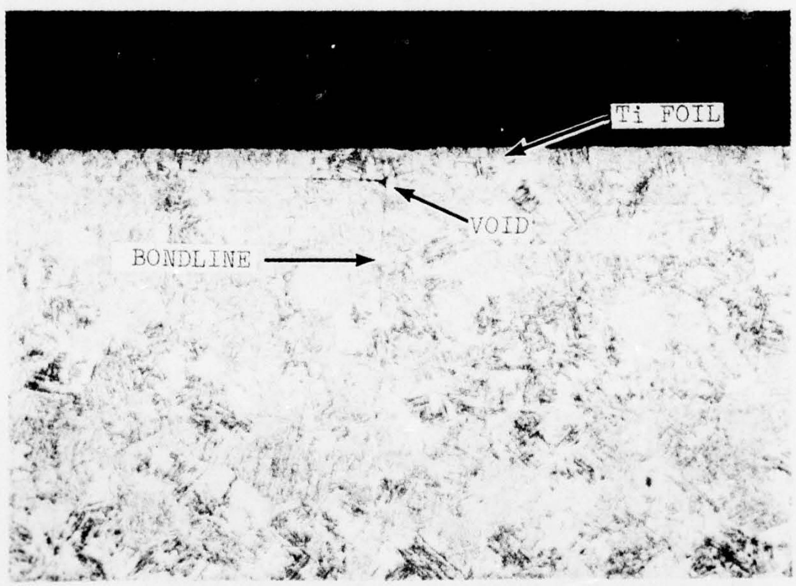


FIGURE 48. CROSS SECTION OF BOND JOINT AREA OF REFERENCE D-SPAR NOTE VOIDS AT VERTEX OF BUTT JOINT AND FOIL JOINT. MAG. 50X.

After diffusion bonding and bend tests, the spar tube was cleaned with hot, (160-180°F) alkaline solution to remove grease and grit, and immersed in 10% hot (140-160°F) nitric acid to desolve the molybdenum foil. Minor sanding was performed adjacent to the flowed metal condition to blend and remove the edges of the foil which are not completely bonded. Sanding was initially performed in a circumferential direction using a flapper wheel disc and subsequently finalized in the longitudinal direction with a continuous belt type sander.

5.2 Pre-form - Tube Spar S/N 7 and 8

As a result of the encouraging data obtained from pre-form S/N 6, two additional pre-forms, S/N 7 and 8 were bonded at Solar with Sikorsky and Army participation. Prior to bonding, modifications to the bonding tool fixture were incorporated. These modifications included machining clearance angles on the edges of the internal mandrel to decrease the chances of any interaction of the titanium and steel, chamfering the edges of the tantalum thermal strip to minimize the metal upset or flow condition, and reworking the bonding fixture with side positioning rails to maintain top plate dimension and alignment. Cleaning of pre-forms S/N 7 and 8 included a double exposure to the nitric-hydrofluoric acid for ten and five minutes as opposed to the two to three minutes used for all the previous pre-forms. The fitup of both pre-forms, S/N 7 and 8, prior to bonding was considered excellent. The parameters and techniques used for pre-form S/N 6 were also used for bonding pre-forms S/N 7 and 8. Visual examination of the spar tubes S/N 7 and 8 after diffusion bonding showed joined units. The titanium foils were bonded the full width of the tantalum thermal strip, both inside and outside along the entire length of the spar tubes. The chamfered edges of the tantalum thermal strips produced slightly less forging action than the previous spar tube, S/N 6. The heat pattern was observed to be uniform and symmetrical along the entire length of the spar tube. Evidence of localized interaction between the titanium pre-form and external wheel electrode was detected at several locations on the external surface of both spar tubes. This localized interaction was the same condition observed on external surface of spar tube S/N 6 and discussed in subsection 5.1 and shown in Figure 40. Bend test results disclose flat fracture areas on one of the two bend test coupons from each of the two spar tubes. The other bend test coupon from each spar tube displayed fracture interfaces granular in nature with no evidence of flat fracturing. The coupons were removed from locations five to six inches from the start and finish ends of the diffusion bonded spar tube as shown in Figure 49. Figure 50 is a view of a typical bend test coupon depicting separation at the diffusion bond joint. Figures 51, 52, 53, and 54 are views of the fracture interface of each of the bend test coupons showing the flat fracture area and granular type fracture surface. The flat fracturing could have been influenced by the location on the spar tube from which the test coupons were removed. Nine inches of material had been added to each end of the original pre-form length at the beginning of the program concept to insure that a minimum of 10 feet would be available for fabrication of the full-scale fatigue test specimen. The flat fracture condition was therefore attributed, at that time, to the proximity to the end of the tube.

Macro-examination of the cross sectional area of both spar tubes showed a general symmetrical heat effected zone extending more than a half inch on either side of the bond joint on both external and internal surfaces. A comparison of cross sections from spar tube S/N 7 and 8 with cross section from spar tube S/N 6 indicates the same general quality, reference Figures 55, 56, and 38. Micro-examination of the cross sectional area of both spar tubes indicate a bond of satisfactory quality for both spar tubes, reference Figures 57 and 58. Comparison with cross sections from other spar tubes indicate that the forging action on spar tubes S/N 7 is less than the forging action on spar tube S/N 6, and S/N 8 but greater than the forging action on the D-Spar reference Figures 47, 48, 57 and 58.

Prior to non-destructive inspection, spar tubes S/N 7 and 8 were alkaline cleaned to remove grease and grit, acid etched to desolve the molybdenum foil, and sanded to blend the edges of the titanium foil. The procedure and method used in cleaning, etching, and sanding were the same as used for spar tube S/N 6.

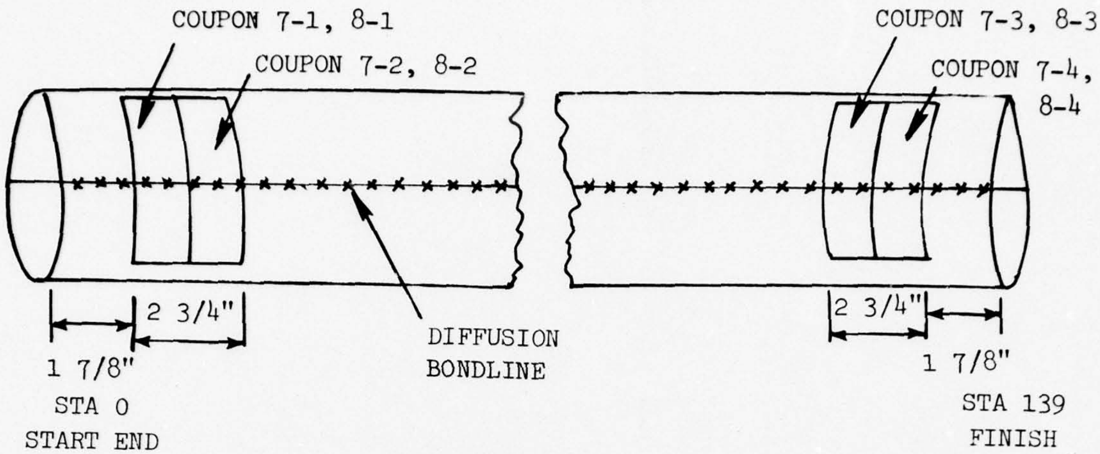


FIGURE 49. SKETCH OF SPAR TUBES S/N 7 & 8 ILLUSTRATING LOCATION OF BEND TEST COUPONS.

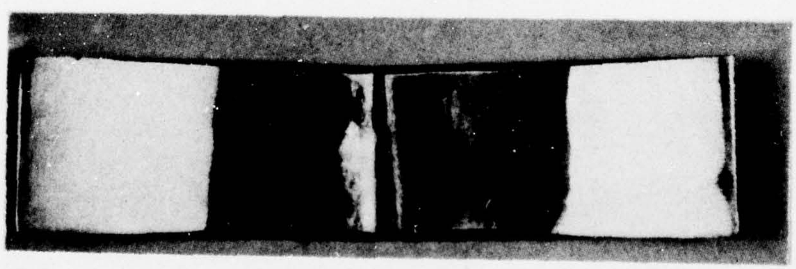


FIGURE 50. TYPICAL BEND TEST COUPON FROM SPAR TUBE S/N 7 & 8, FRACTURE AT BOND JOINT AS ANTICIPATED.

FIGURE 51. **FRACTURE INTERFACE OF BEND TEST COUPON** S/N 7-2.
(START END) NOTE FLAT FRACTURE AREA. MAG. 2X.

FIGURE 52. **FRACTURE INTERFACE** OF **BEND TEST** COUPON S/N 7-3.
(FINISH END) NOTE FLAT FRACTURE AREA. MAG. 2X.

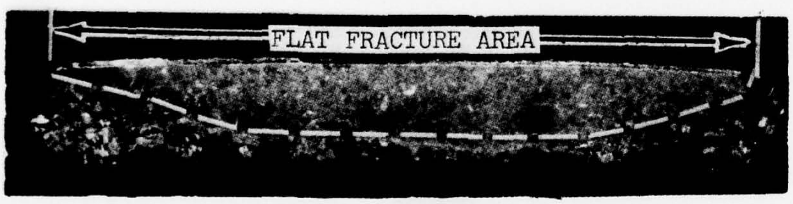


FIGURE 53. **FRACTURE INTERFACE OF BEND TEST** COUPON S/N 8-2.
(START END) NOTE FLAT FRACTURE AREA. MAG. 2X.

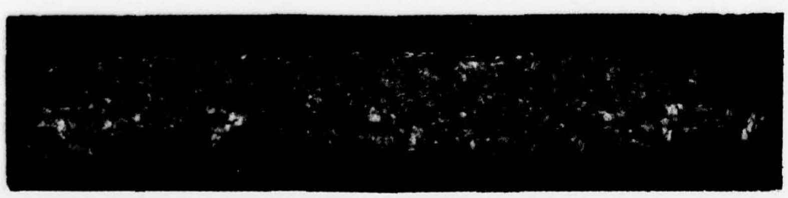


FIGURE 54. FRACTURE INTERFACE OF BEND TEST COUPON S/N 8-3.
(FINISH END) NOTE GRANULAR TYPE INTERFACE. MAG. 2X.

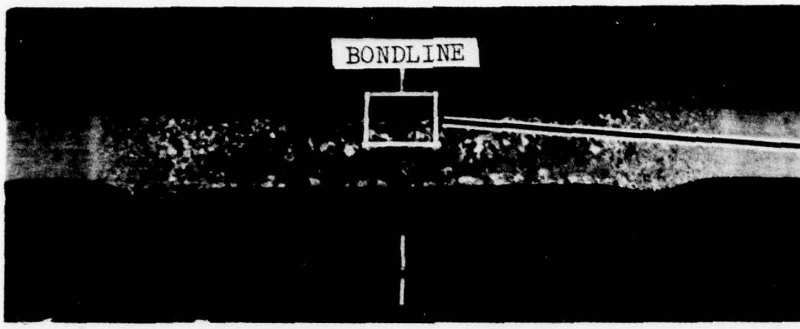


FIGURE 55. CROSS SECTION OF SPAR TUBE S/N 7-1 ILLUSTRATING SYMMETRICAL HEAT EFFECTED ZONE. (START END) MAG. 3X.

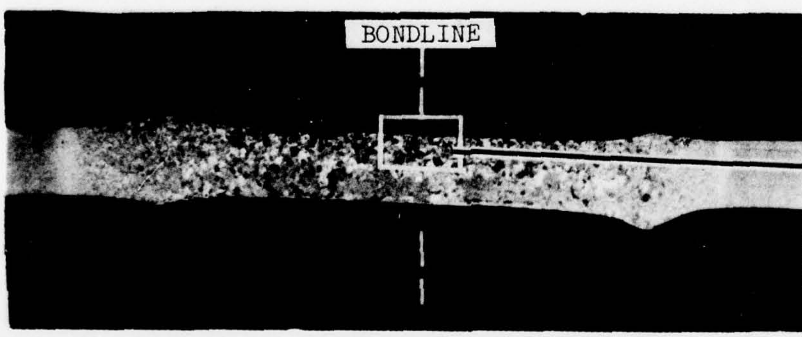
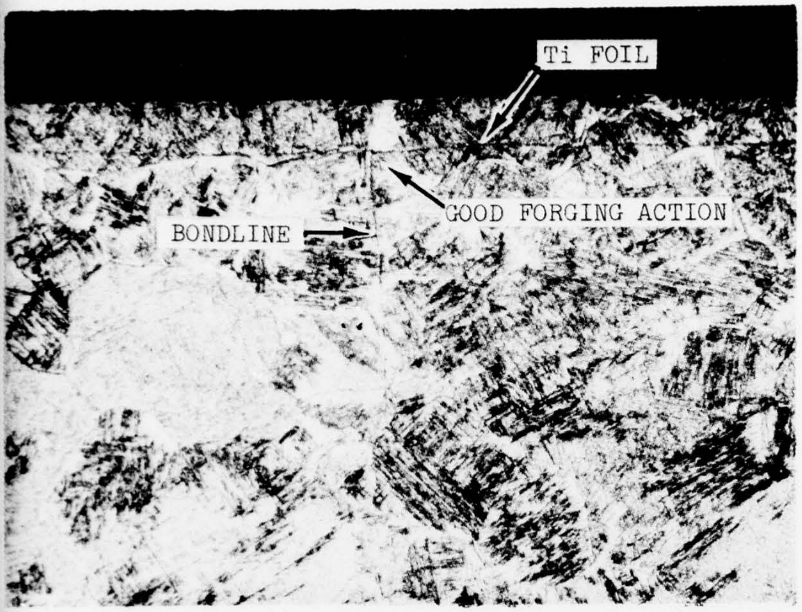
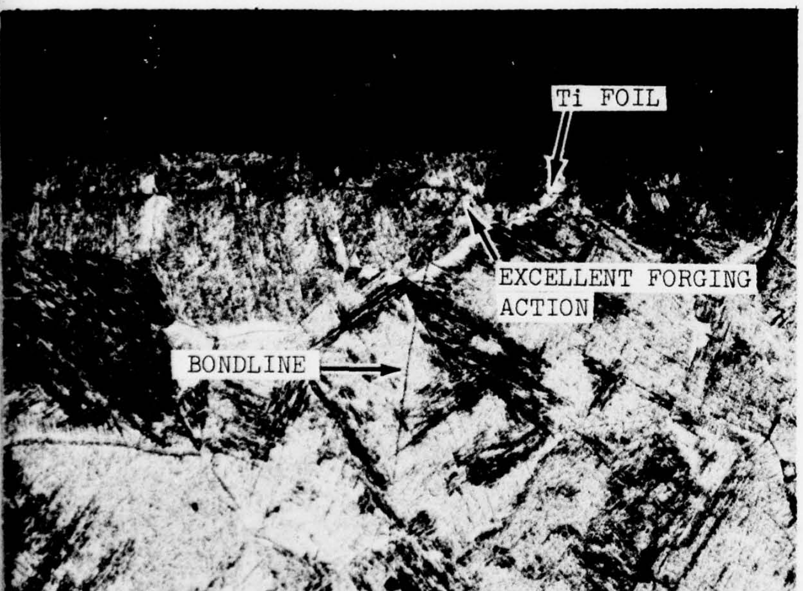


FIGURE 56. CROSS SECTION OF SPAR TUBE S/N 8-1 ILLUSTRATING SYMMETRICAL HEAT EFFECTED ZONE. (START END) MAG. 3X.



RE 57. CROSS SECTION OF BOND JOINT AREA SPAR TUBE S/N 7-1. (START END) MAG. 50X.



RE 58. CROSS SECTION OF BOND JOINT AREA SPAR TUBE S/N 8-1. (START END) MAG. 50X.

2

6.0 NON-DESTRUCTIVE INSPECTION OF TITANIUM SPAR TUBES

Visual, borescope, fluorescent penetrant, radiographic, and ultrasonic inspection of spar tubes S/N 6, 7 and 8 were conducted. No evidence of voids, nonbonding, or lack of diffusion were detected in the bond joint. However, in certain areas along the external and internal surfaces of the pre-form, manufacturing defects were observed. These defects consisted of linear abnormalities along the flowed metal area, and local anomalies on the flat area adjacent to the flowed metal between the flowed metal and the bond joint. The manufacturing defects occurred during the CSDB operation and were due to interaction between the titanium pre-form and the adjacent steel tooling.

6.1 Borescope, Fluorescent Penetrant, and Radiographic Inspection

Borescope inspection of the internal area of the three spar tubes at a magnification of five, 5X, revealed linear and localized defects. The linear abnormalities, four to six inches in length, were observed on two of the spar tubes, S/N 7 and 8 and were similar to the linear interaction abnormality observed previously on the external surface of spar tube S/N 6 illustrated in Figure 39 and discussed in Section 5.0. The cause of these linear interaction abnormalities is attributed to the steel mandrel contacting the titanium pre-form or titanium foil during the bonding operation. The localized anomalies were observed on all three spar tubes and were determined to be the same defects observed previously on the external surface of the spar tubes and shown in Figure 40. That is, the localized anomalies observed on the external surface extend through the wall thickness of the spar tubes. The shrinkage cracking observed within the localized anomaly on the external surface of the spar tubes was also evident on the external surface of the spar tubes was also observed on the internal surface thus, denoting that the shrinkage cracking were through cracks. Table IV summarizes the type and location of each of the observed manufacturing defects in each of the spar tube. The borescope inspection also disclosed the existance of a crazing appearance across the flowed metal in the area of the linear interaction abnormality. No defects were. detected by borescope inspection along the longitudinal bond joint of the spar tubes. Fluorescent penetrant inspection in accordance with MIL-I-6866A was performed on both the external and internal surfaces. No evidence of cracking or voids was detected in the bond area or along the flowed metal, except for the through cracking condition observed previously and shown in Figure 40. The crazing condition across the flowed metal was not detected by fluorescent penetrant. Radiographic inspection in accordance with MIL-STD-453(1) was performed. No evidence of cracking or voids was found in the bond area. Both the linear and localized interaction conditions observed on the internal and external surfaces were observed in areas adjacent to the bond joint. Figures 59 and 60 are photographs of x-rays depicting the two interaction conditions on the internal and external spar tube surfaces. The crazing condition along the flowed metal area observed during fluorescent penetrant inspection was also detectable in radiographic inspection and is illustrated in Figure 60.

TABLE IV

SUMMARY OF MANUFACTURING DEFECTS OBSERVED IN FABRICATED CSDB SPAR TUBES

SPAR TUBE S/N	TYPE OF DEFECT ①	LOCATION OF DEFECT (INCHES FROM START END)	SURFACE LOCATION
6	A	34	External
6	B	0-6	External
6	B	6-8	Internal
7	A	118	External
7	B	33-39	Internal
8	A	33	External
8	A	71	External
8	B		

① A - Linear interaction condition along flowed metal, without through cracking, Figure 39

B - Localized interaction condition adjacent to flowed metal with through cracking, Figure 40.

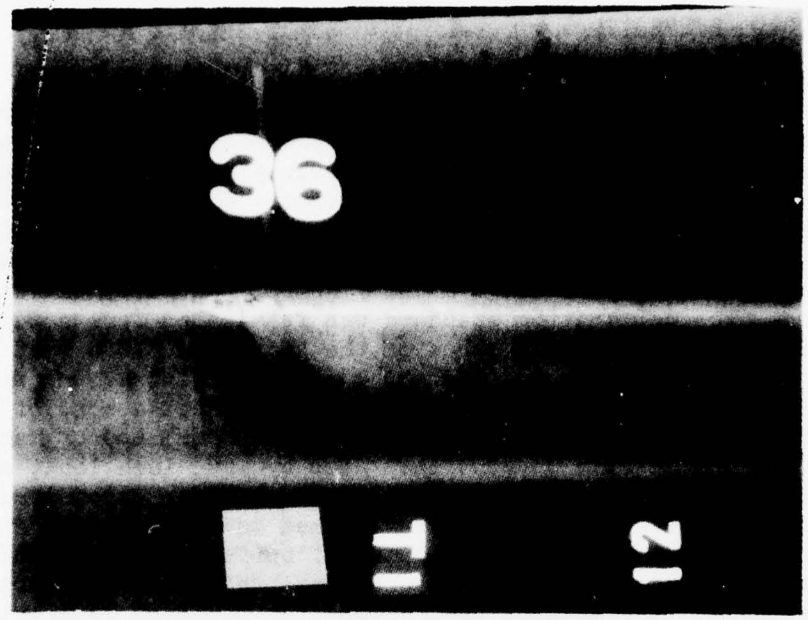


FIGURE 59. PHOTOGRAPH OF X-RAY DEPICTING INTERACTION CONDITION IN FLOWED METAL AREA ON INTERNAL SURFACE OF PRE-FORM S/N 7. MAG. 3X.

FIGURE 60. PHOTOGRAPH OF X-RAY OF INTERACTION CONDITION ON FLAT AREA ADJACENT TO METAL FLOW CONDITION ON EXTERNAL SURFACE OF PRE-FORM TUBE S/N 6, REFERENCE FIGURE 40. NOTE CRAZING CONDITION IN FLOWED METAL AREA. MAG. 3X.

6.2 Ultrasonic Inspection

Prior to detail ultrasonic inspection of the bonded spar tubes, a calibration standard was fabricated and a feasibility study was performed. Fabrication of the calibration standard and performance of the feasibility study was accomplished by Nuclear Energy Services, Inc., an Automation Industries, Inc., Company, Danbury, Connecticut. The ultrasonic technique used for inspection was a pulse-echo immersion method equipped with a direct read-out C-scan which manifest signals from the bond area above the sensitivity setting of a known anomaly as calibrated by the calibration standard. The calibration standard was fabricated from a two inch wide elliptical ring cut from an area of the spar tube S/N 6 that had been evaluated by bend tests and visual, borescope, fluorescent penetrant, and radiographic inspections, and considered to exhibit a bond of excellent quality. Fabrication of the calibration standard consisted of machining two notches, .005 inch wide by .010 inch deep by .063 inch long, at the bonded joint, in two locations along the two inch width dimension, approximately one inch apart. One notch was machined on the external surface while, the other was machined on the internal surface. The notches simulate defects in the bond and will be used to standardize all inspections on CSDB spar tubes. A sketch of the calibration standard is provided in Figure 61. The feasibility study successfully demonstrated the practicality of ultrasonically inspecting CSDB spar tubes and to readily detect the notches in the standard.

The procedure established in the feasibility study and used in the inspection of spar tubes S/N 6, 7, and 8 involved the use of a pulse-echo water immersion technique in 45° angle beam and 90° longitudinal modes by means of automated search unit. The search unit directed a pulse beam, 45° angle or 90° normal, contingent upon inspection mode, through the water to the flat surface of the spar tube. A total of five inspections in three modes were performed. These modes included the following inspections: Two circumferential shear inspections at 45° attitude from both the right and left sides of the spar tube to detect defects or nonbond condition in the bond joint, two axial shear inspections at 45° attitude from the force and aft directions of the spar tube to detect any anomalies transverse to the bond joint, and one longitudinal inspection at 90° attitude, normal to the external surface to detect any nonbonding or defect between the external titanium foil and the external surface of the spar tube, or between the internal titanium foil and the internal surface of the spar tube. The circumferential shear mode and the axial shear mode are basically the same type inspection, i.e., the shear waves are transmitted along the wall thickness of the spar tube detecting defects in the bond joint. The longitudinal inspection mode is distinctly different. In this inspection mode, the waves enter the spar tube normal to the surface, pass through the wall thickness, and are reflected off the back wall on the opposite side of the spar tube. A nonbond or defect is depicted by a loss of signal. The five inspection operations are depicted diagrammatically in Figure 62. Three principal echo signals appear on the reflectoscope during inspection: an echo from the water-

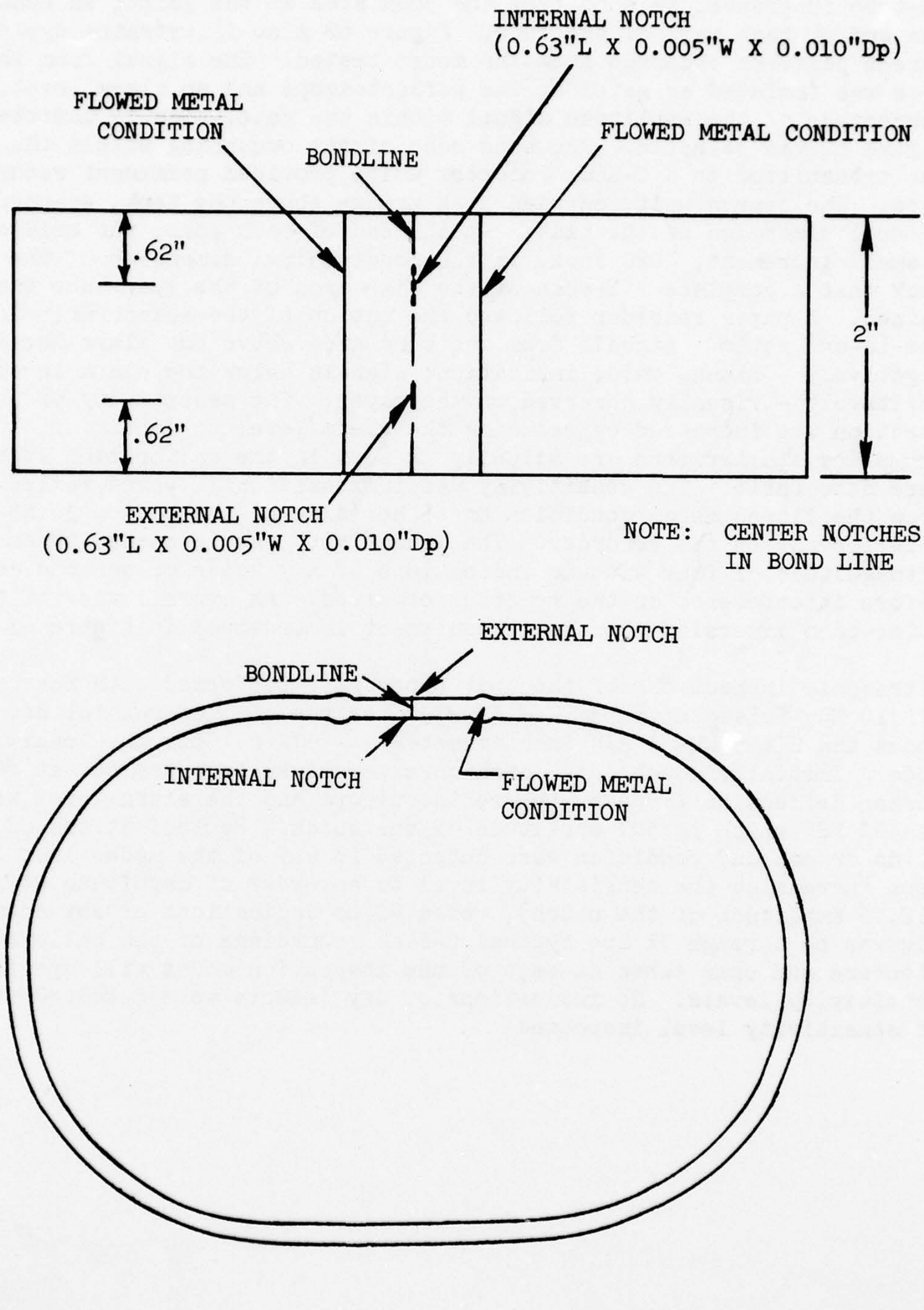


FIGURE 61. CALIBRATION STANDARD FOR ULTRASONIC INSPECTION OF CSDB SPAR TUBE.

to-tube interface; an echo from the bond area at the joint; an echo from the end or back wall of the tube. Figure 62 also illustrates typical screen patterns observed from the modes tested. The signal from the bond area was isolated or gated on the reflectoscope and an alarm level, a percentage of the amplitude signal within the gate, also illustrated in Figure 62 was selected. The bond echo signal occurring within the gate was transmitted to a C-scan recorder which provided permanent record read-outs. The search unit, carried by a bridge above the tank, scanned in the lateral dimension of the tank. At the end of each scan, the bridge indexed a small increment, .020 inch, in the longitudinal dimension of the tank, such that a complete X Y-scan of the flat area of the spar tube was obtained. A paper recorder followed the motion of the search unit in a one-to-one ratio. Signals from the bond area above the alarm level record negatively - blank, void, indication; signals below the alarm level record positively - visually observed on the paper. The sensitivity of the inspection was increased by reducing the alarm level to detection, i.e., anomalies smaller than are actually present in the calibration standard were detectable. The sensitivity was increased until waves reflected from the flowed metal condition on either side of the bonded joint caused interference on the recorder. The sensitivity was increased by an order of magnitude of four with no indications of any voids or nonbond condition before interference on the recorder occurred. An overall view of the pulse-echo immersion ultrasonic equipment is provided in Figure 63.

Ultrasonic inspections of the spar tubes were performed with Search Units SIL 10 MH_Z pulsed at 5 MH_Z --- 57A2790 for the circumferential and axial modes and SIL 5 MH_Z / 3/4 inch diameter --- 57A2694 for the longitudinal mode. Initially notch 'A', notch on external surface was set at 80% full screen deflection (FSD) on the reflectoscope and the alarm level was set at 40% FSD which is 50% amplitude of the notch. No indications of any voids or nonbond condition were detected in any of the modes inspected. Upon increasing the sensitivity level to an order of magnitude of four (12.5% amplitude of the notch), revealed no indications of any anomalies. Figures 64 through 71 are typical C-scan recordings of the calibration standard and spar tubes at each of the inspection modes will specific sensitivity levels. No indications of any defects were detected at any of sensitivity level inspected.

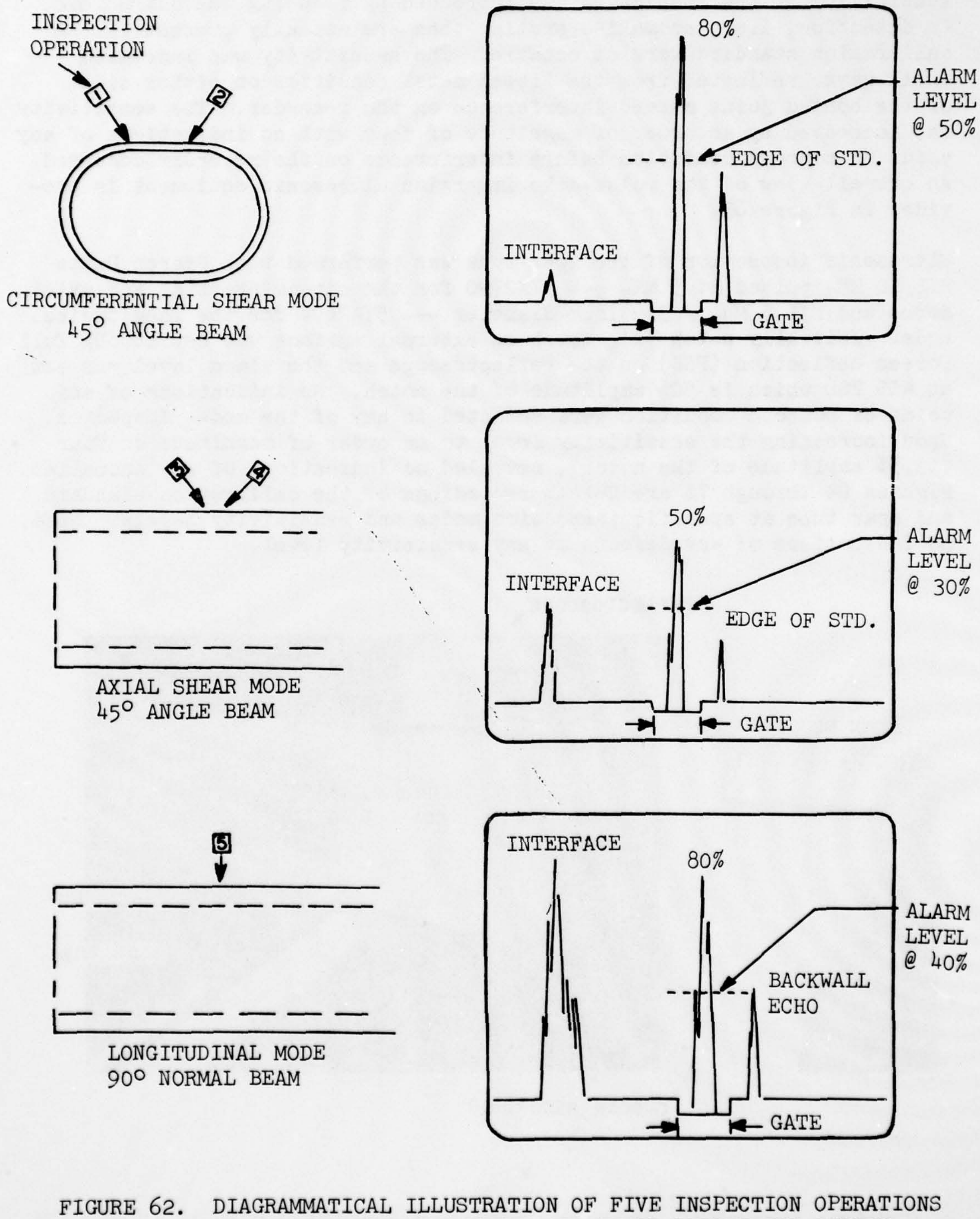


FIGURE 62. DIAGRAMMATICAL ILLUSTRATION OF FIVE INSPECTION OPERATIONS IN THREE ULTRASONIC MODES AND THEIR RESPECTIVE SCREEN PATTERN OBSERVED ON THE REFLECTOSCOPE.

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ESTABLISHMENT OF MANUFACTURING METHOD AND TECHNOLOGY FOR THE FA--ETC(U)
NOV 78 M J BONASSAR, J J LUCAS DAAG46-76-C-0016
UNCLASSIFIED SER-510010 AVRADCOM-TR-79-5 NL

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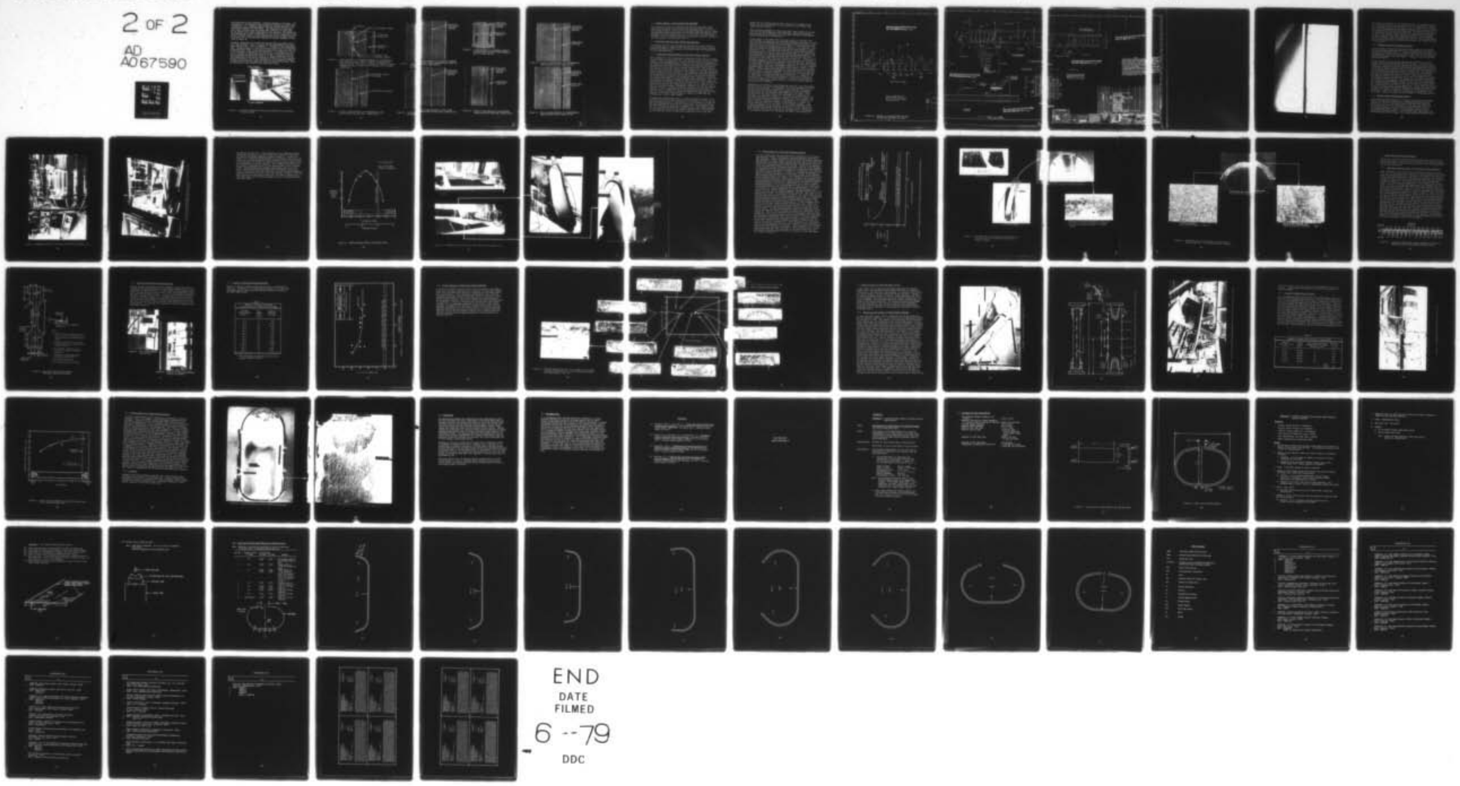

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the alarm level record positively - visually observed on the paper. The sensitivity of the inspection was increased by reducing the alarm level to detection, i.e., anomalies smaller than are actually present in the calibration standard were detectable. The sensitivity was increased until waves reflected from the flowed metal condition on either side of the bonded joint caused interference on the recorder. The sensitivity was increased by an order of magnitude of four with no indications of any voids or nonbond condition before interference on the recorder occurred. An overall view of the pulse-echo immersion ultrasonic equipment is provided in Figure 63.

Ultrasonic inspection of the spar tube was performed with Search Units SIL 10 MH_Z pulsed at 5 MH_Z --- 57A2790 for the circumferential and axial modes and SIL 5 MH_Z / 3/4 inch diameter --- 57A2694 for the longitudinal mode. Initially notch 'A', notch on external surface was set at 80% full screen deflection (FSD) on the reflectoscope and the alarm level was set at 40% FSD which is 50% amplitude of the notch. No indications of any voids or nonbond condition were detected in any of the modes inspected. Upon increasing the sensitivity level to an order of magnitude of four (12.5% amplitude of the notch), revealed no indications of any anomalies. Figures 64 through 71 are C-scan recordings of the calibration standard and spar tube at specific inspection modes and sensitivity levels. Note, no indications of any defects at any sensitivity level.

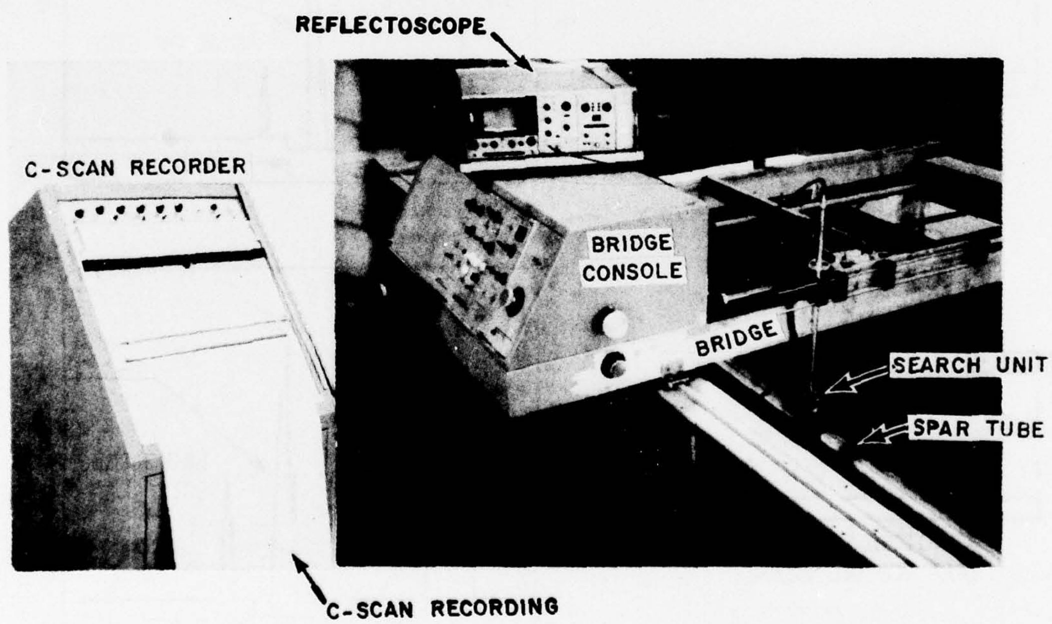


FIGURE 63. PULSE-ECHO IMMERSION ULTRASONIC EQUIPMENT USED IN INSPECTION OF CSDB SPAR TUBE.

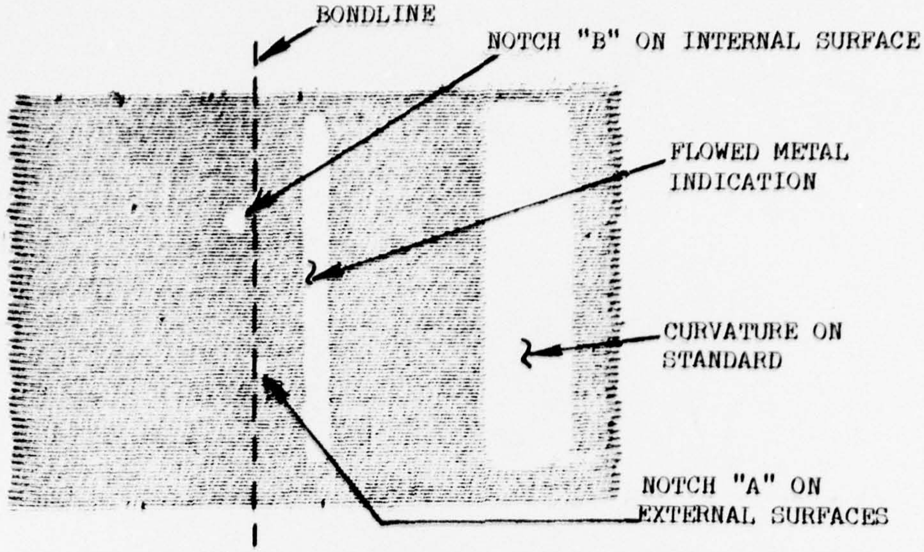


FIGURE 64. C-SCAN RECORDING OF CALIBRATION STANDARD IN CIRCUMFERENTIAL SHEAR INSPECTION MODE. NOTCH "A" 80% FSD, ALARM 40% FSD. (NOTE INDICATIONS OF NOTCHES ON EXTERNAL AND INTERNAL SURFACES. INTERNAL INDICATION PRINTS-OUT OFF BONDLINE DUE TO INTERNAL PROJECTION).

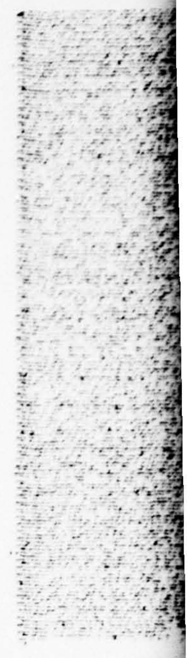


FIGURE 65. C-SCAN
IN AXI
80% FS

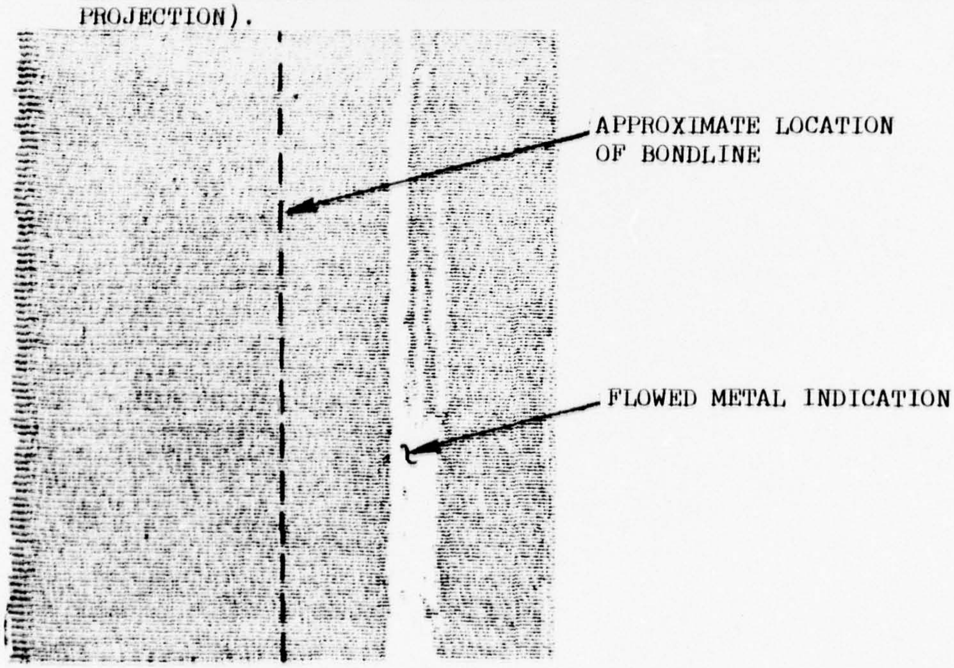


FIGURE 67. TYPICAL C-SCAN RECORDING OF CIRCUMFERENTIAL SHEAR INSPECTION MODE ON SPAR TUBE. ALARM 40% FSD.

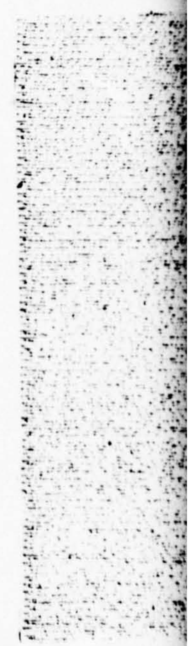
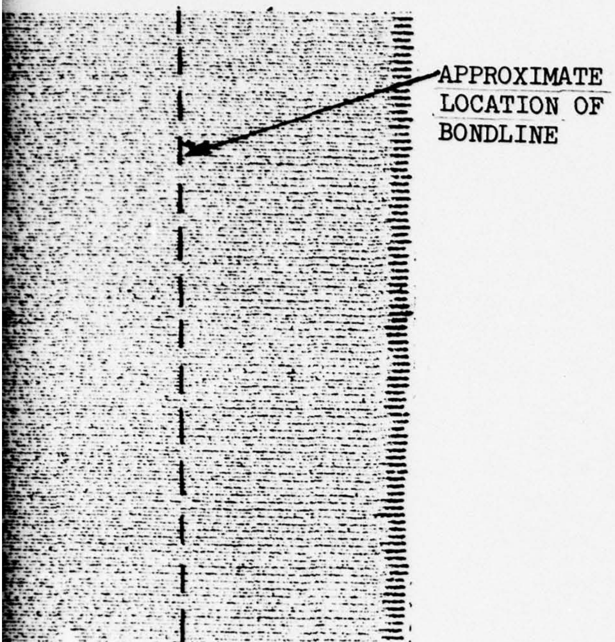


FIGURE 68. TYPICAL
INSPECTI



-SCAN RECORDING OF CALIBRATION STANDARD
N AXIAL SHEAR INSPECTION MODE, NOTCH "A"
0% FSD, ALARM 40% FSD.

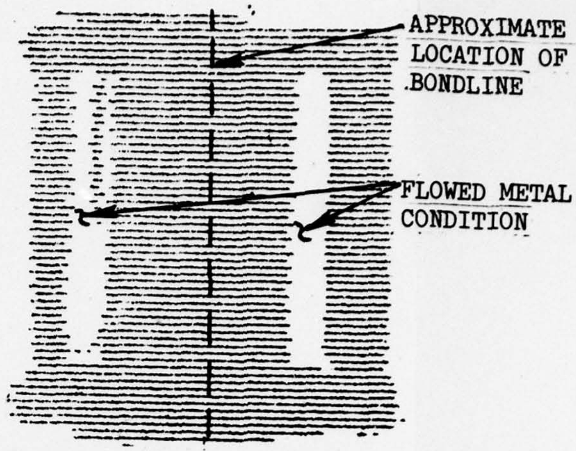
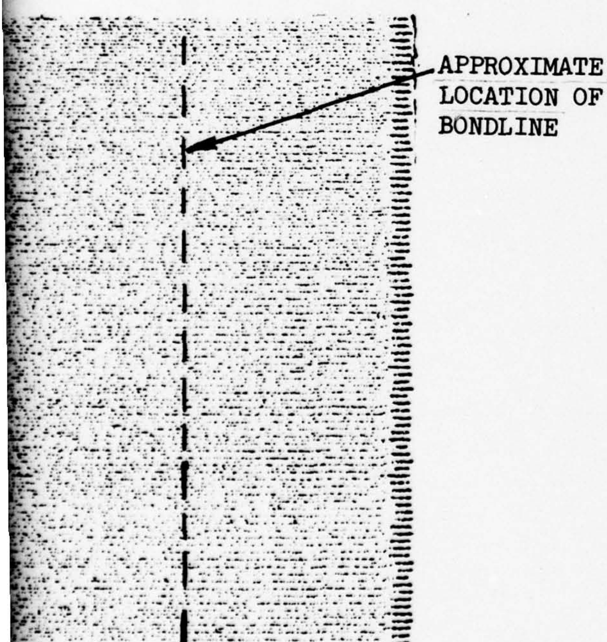


FIGURE 66. C-SCAN RECORDING OF CALIBRATION STANDARD IN LONGITUDINAL INSPECTION MODE, NOTCH "A" 80% FSD, ALARM 40% FSD.



CAL C-SCAN RECORDING OF AXIAL SHEAR
CTION MODE ON SPAR TUBES, ALARM 40% FSD.

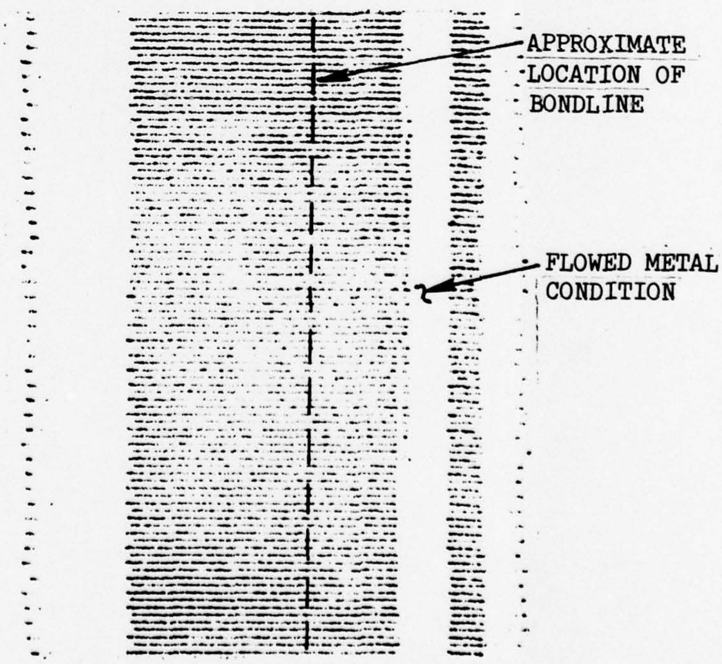


FIGURE 69. TYPICAL C-SCAN RECORDING OF LONGITUDINAL INSPECTION MODE ON SPAR TUBE, ALARM 40% FSD.

2

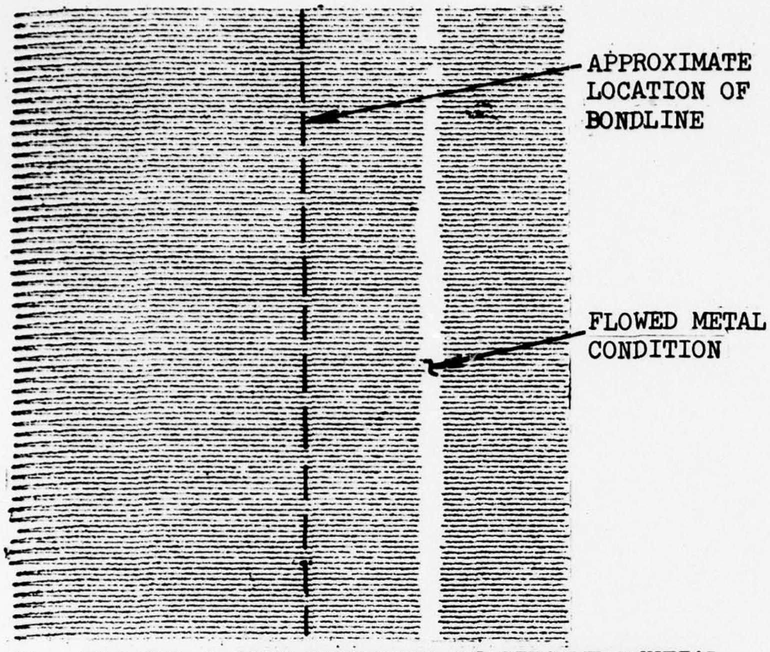


FIGURE 70. TYPICAL C-SCAN RECORDING OF CIRCUMFERENTIAL SHEAR INSPECTION MODE, ALARM 20% FSD.

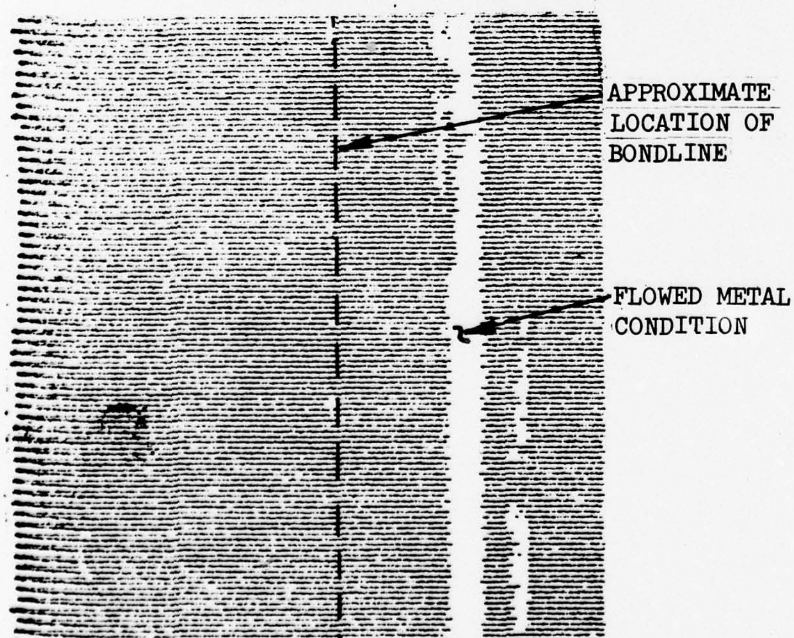


FIGURE 71. TYPICAL C-SCAN RECORDING OF CIRCUMFERENTIAL SHEAR INSPECTION MODE, ALARM 10% FSD.

7.0 FATIGUE TESTING - CSDB TITANIUM SPAR SPECIMENS

One full-scale ten foot long UH-60A BLACK HAWK spar specimen, twelve small-scale specimens, and one D-spar were fatigue tested. The full-scale fatigue testing of the ten foot long BLACK HAWK spar and the D-spar were performed under steady axial and vibratory edgewise bending at loads intended to initiate cracking in 1 to 3 X 10^6 cycles. The small-scale specimens fatigue testing was performed in tension--tension to failure or 1 X 10^7 cycles at a stress ratio of R = 0.1.

7.1 Full-Scale, Ten-foot CSDB Titanium Spar Specimen

A full-scale ten foot test specimen was fabricated from spar tube S/N 7 and fatigue tested. Results of the testing show that diffusion bonding produces satisfactory joint quality, well above flight load requirements for the spar application.

7.1.1 Preparation and Fabrication of Full-Scale Fatigue Specimen

Upon completion of the non-destructive inspection methods used to evaluate the spar tubes, one spar tube, S/N 7 was selected to be full-scale fatigue tested. Prior to fabrication of the full-scale fatigue test specimen, in accordance with EWR-50000 Drawing, Figure 72, the localized anomaly, which was produced by the interaction of the wheel electrode and the titanium pre-form at a weld defect in the tantalum thermal strip, and located on the flat area of the spar adjacent to the flowed metal, between the flowed metal and the bondline at station 118, was repaired. This type anomaly is shown in Figure 40, spar tube S/N 6. The anomaly was considered potentially detrimental to the fatigue characteristics of the spar and corrective action was deemed required. The corrective action consisted in removing the anomaly by drilling a half-inch diameter hole, inserting a plug of the same diameter and material, Ti-6Al-4V, and securing the plug in place by manual plasma arc welding using Ti-6Al-4V filler wire. After welding, the external and internal weld surfaces were blended to the contour of the spar by localized grinding. Radiographic inspection of the weld area was performed in order to ascertain that the quality of the weld was satisfactory. Prior to committing the full-scale fatigue test specimens to this weld repair procedure, a trial tube segment from spar tube S/N 5 was subjected to the above cited procedure in order to conform that the technique was a viable repair method.

An additional manufacturing defect, a linear abnormality located on the internal surface of the spar was observed from station 33 to 39, and has been discussed previously in subsection 6.1 and illustrated in Figure 59. The linear abnormality was along the flowed metal area occurring during the CSDB operation and discussed in Reference (d). The abnormality was due to an interaction between the titanium pre-form and internal mandrel at a possible weld defect in the tantalum thermal strip. The condition was also observed during non-destructive inspection of the spar tube.

Because of its distance from the end of the tube, the length of the defect, and the non-existence of thru cracking, it was decided that repair was not required.

After successful completion of the plug repair creep forming of the spar tube into the BLACK HAWK main rotor blade spar contour was achieved. Creep forming was accomplished using the same techniques and procedures described previously in subsection 3.2.

During removal of the Turko inert film and cleaning of the spar after creep forming in preparation for fluorescent penetrant inspection, a black smut condition was detected along the diffusion bonded joint area on the external surface of the spar as shown in Figure 73. The black smut could easily be removed by rubbing with a scrub brush or a mild abrasive. However, the black smut re-appears when the spar tube was cleaned in nitric-hydrofluoric acid. Initially this condition was attributed to residual molybdenum from the moly foil used as a parting agent in the CSDB process and subsequently not removed during the previous cleaning operation. Attempts were made to eliminate the black smut condition with hot nitric acid which is the normal method of removing the moly foil. However, after continual exposure to the hot nitric acid, the condition still existed. Localized sandblasting and mild sanding in the area were also unsuccessful in eliminating the black smut condition. Review of spar tube S/N 8 showed the same general condition. Macrographic inspection of the smut condition suggested that it was possibly associated with selected etching of large grains. Electron probe micro-analysis on areas exhibiting the black smut condition and on areas not exhibiting the condition revealed no significant difference in chemical elements. Scanning Electron Microscopy, SEM of these areas disclosed different grain orientation to a depth of .004 to .010 inches. A hardness profile taken of a cross-section showed no significant trend. The observed black smut condition was determined to be due to crystalographic grain structure. No adverse effects were expected from this condition.

Subsequent to successfully creep forming spar tube S/N 7 into the desired airfoil contour and prior to installation of the end attachment fittings, the spar was shot peened. Shot peening of both internal and external surface of the spar was performed in accordance with the requirements and techniques for the production BLACK HAWK main rotor spar. Final buildup of the full-scale fatigue test specimens was accomplished in accordance with EWR 50000, Figure 72. Fabrication entailed cutting .008 inch thick fiberglass pre-impregnated material into various lengths from sixteen inches to thirty-one inches, in increments of 0.1 inches for a total cumulative laminated thickness of approximately 1.5 inches, involving more than 160 plies for each of four laminate packages. After curing the laminates in an autoclave, one each of the four buildup laminate packages were bonded to each end of the spar, top and bottom surfaces prior to drilling the holes for the attachment cuffs. The purpose of the laminate buildups is to strengthen the ends of the specimen for

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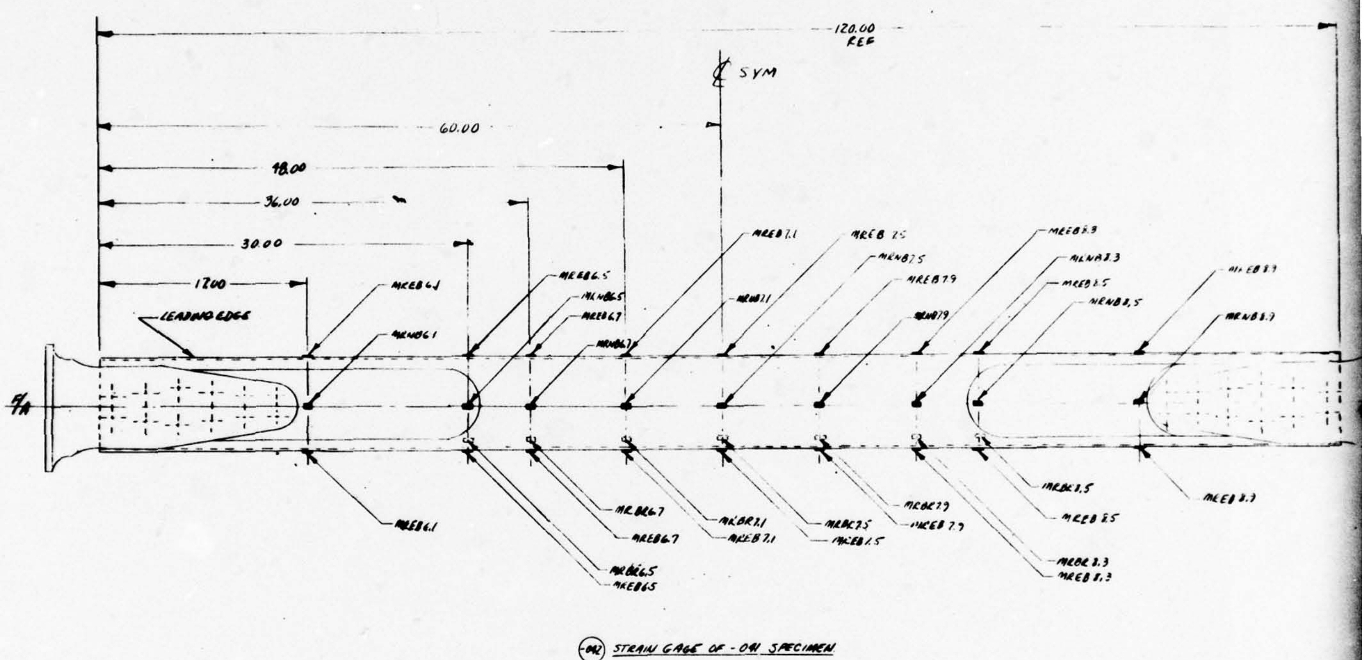


GAGE LOCATION	GAGE TYPE FIBERGLASS	TITANIUM
BR		WK-05-250BG-350
NB&EB	WK-03-250DM-350	" " "

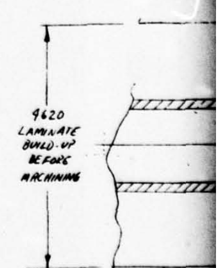
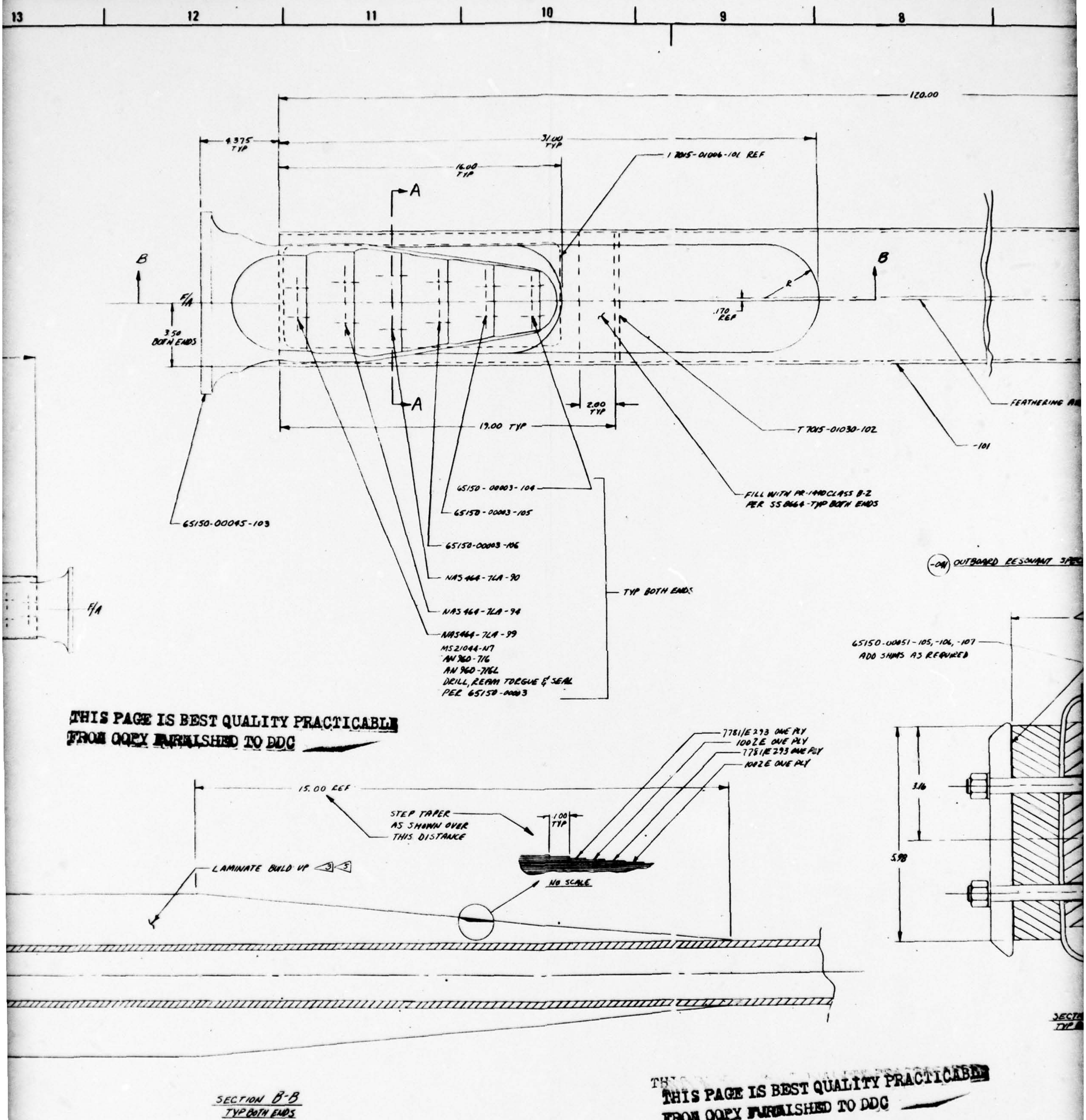


FIGURE 72. DRAWING OF FULL-SCALE TEN FOOT SPAR
FATIGUE TEST SPECIMEN, EWR 50000.



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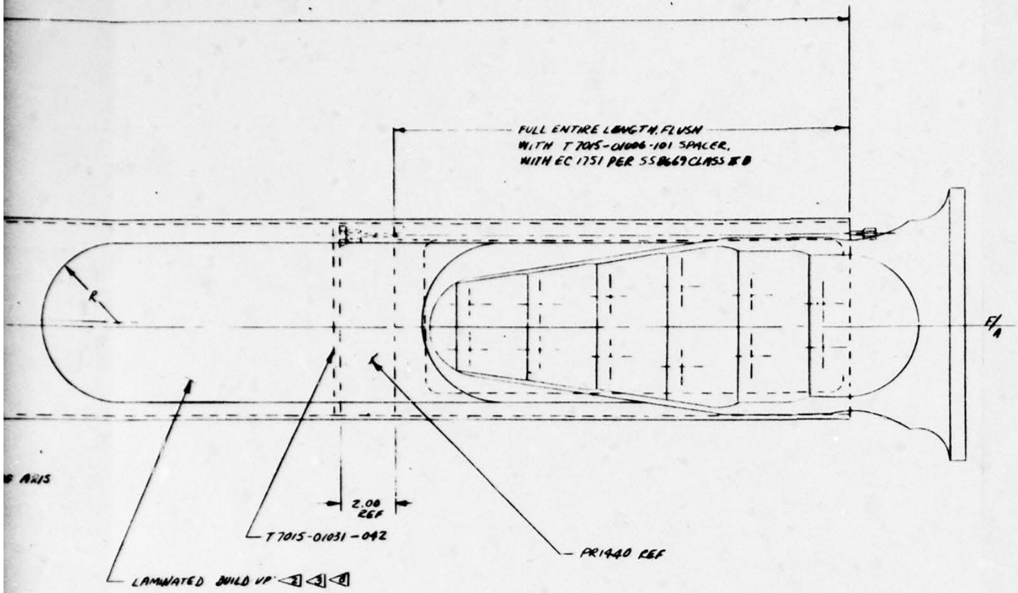
DWG NO EWR 50000 SHEET 2

7 6 5 4 3 2



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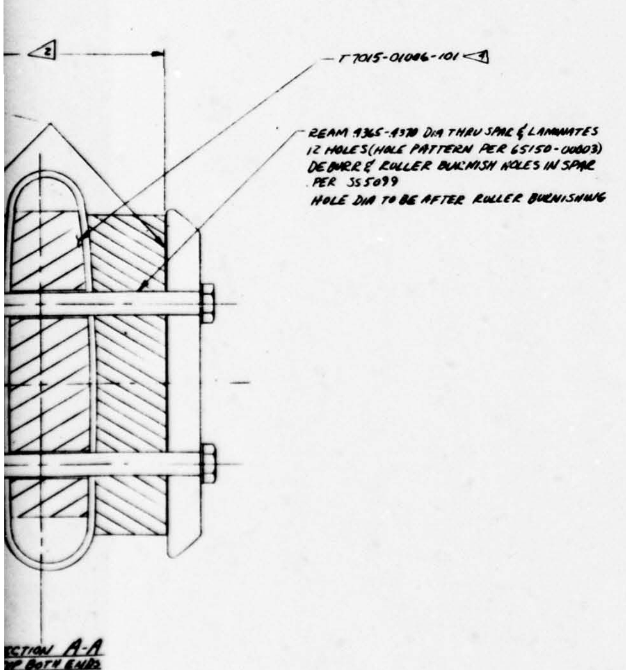
SPECIMEN



SECTION A-A
TYP BOTH ENDS

NOTES:

1. BREAK ALL SHARP EDGES .005-.015 INCH RADIUS UNLESS
2. MACHINE FIBERGLASS LAMINATED BUILDUP .020-.030 BELOW DIMENSION. DIMENSION SHOWN TO BE SYMMETRICAL
3. FIBERGLASS LAMINATED BUILD-UP TO START WITH (.0095 THK) AGAINST BLADE AND TO ALTERNATE WITH (.0092 THK) TO FINAL DIMENSIONS SHOWN IN F/D. STEP BUILD-UP WHILE ALTERNATING PLIES AS SHOWN
4. SURFACES OF T7015-01006-101 SPACERS TO BE FITTED OF SPAR WITHIN 0 TO .005 CLEARANCE
5. NB GAGES ARE FLATWISE BENDING BRIDGES (UPPER & LOWER ARE EDGE WISE BENDING BRIDGES (L.E. & T.E. LOCATIONS). ALL ARE SINGLE ACTIVE.
6. ALL STRAIN GAGING TO BE DONE AFTER FABRICATION
7. ALL STRAIN GAGES, SOLDER TABS, WIRE AND RELATED BE PRODUCED BY THE ENGR INSTRUMENTATION LABORATORY
8. SPAR TO BE PREBOND PER SS 8461. PRIME WITH SS PER SS 8612. LAMINATED BUILDUP TO BE BONDED TO SS8612-002 ADHESIVE PER SS 8612

QTY	QTY	QTY	QTY	SYMBOLS	CODE IDENT NO	PART NUMBER	NOMENCLATURE	SPECIFICATION	STOCK SIZE	MATERIAL OR
		A/R		5,6,7		INSTRUMENTATION	MATERIALS (WIRE, GAGES, ETC)			
			A/R			65150-00051-107	SHIM			
			A/R			65150-00051-106	SHIM			
			A/R			65150-00051-105	SHIM			
			A/R		99891	PR1440 CLASS B-2	COMPOUND	SS 8664		
			A/R		76381	EC1751	COMPOUND	SS 8669		
			A/R	2,3	04963	1002E	SCOTCHPLY (.0092" THK)	SS 9610		
			A/R	2,3	04963	7781/E293	SCOTCHPLY (.0095" THK)	SS 9610		
			A/R			AN960-716L	WASHER			
			A/R			AN960-716	WASHER			
			2	4		T7015-01006-101	SPACER			
			1			T7015-01031-042	PLATE ASSY			
			1			T7015-01030-102	PLATE			
			4		15653	MS21044-N7	NUT			
			2			65150-00045-103	CUFF			
			4			NAS464-7LA-95	BOLT			
			4			NAS464-7LA-94	BOLT			
			4			NAS464-7LA-90	BOLT			
			4			65150-00003-106	BOLT			
			4			65150-00003-105	BOLT			
			4			65150-00003-104	BOLT			
						EWR 50000-042	STRAIN GAGE SPECIMEN			
			1			EWR 50000-101	SPAR (CSDB 10-FT TITANIUM SPAR TUBE)			
		1				EWR 50000-041	SPAR FATIGUE SPECIMEN			
		042	041	← DASH NO						

LIST OF MATERIAL AND PARTS LIST

APPLICATION OF PROTECTIVE FINISHES
APPLICABLE TO DASH NUMBERS

APPLICABLE INSPECTION TEST PLAN DRAWING NUMBER

INSPECTION REQUIREMENTS

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ORIGINALLY PREPARED UNDER CONTRACT NUMBER

RELEASE AUTHORITY

TASK MANAGER DATE 4-12-78

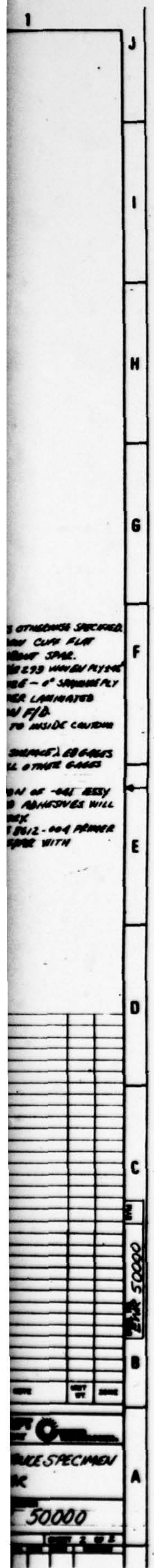
RELEASE GROUP DATE

GOVERNMENT DATE

SIKORSKY AIRCRAFT
STRATFORD, CONNECTICUT

DRAWING TITLE
OUTBOARD RESON
CSDB SP

SIZE J
FSCM NO. 78286
EWR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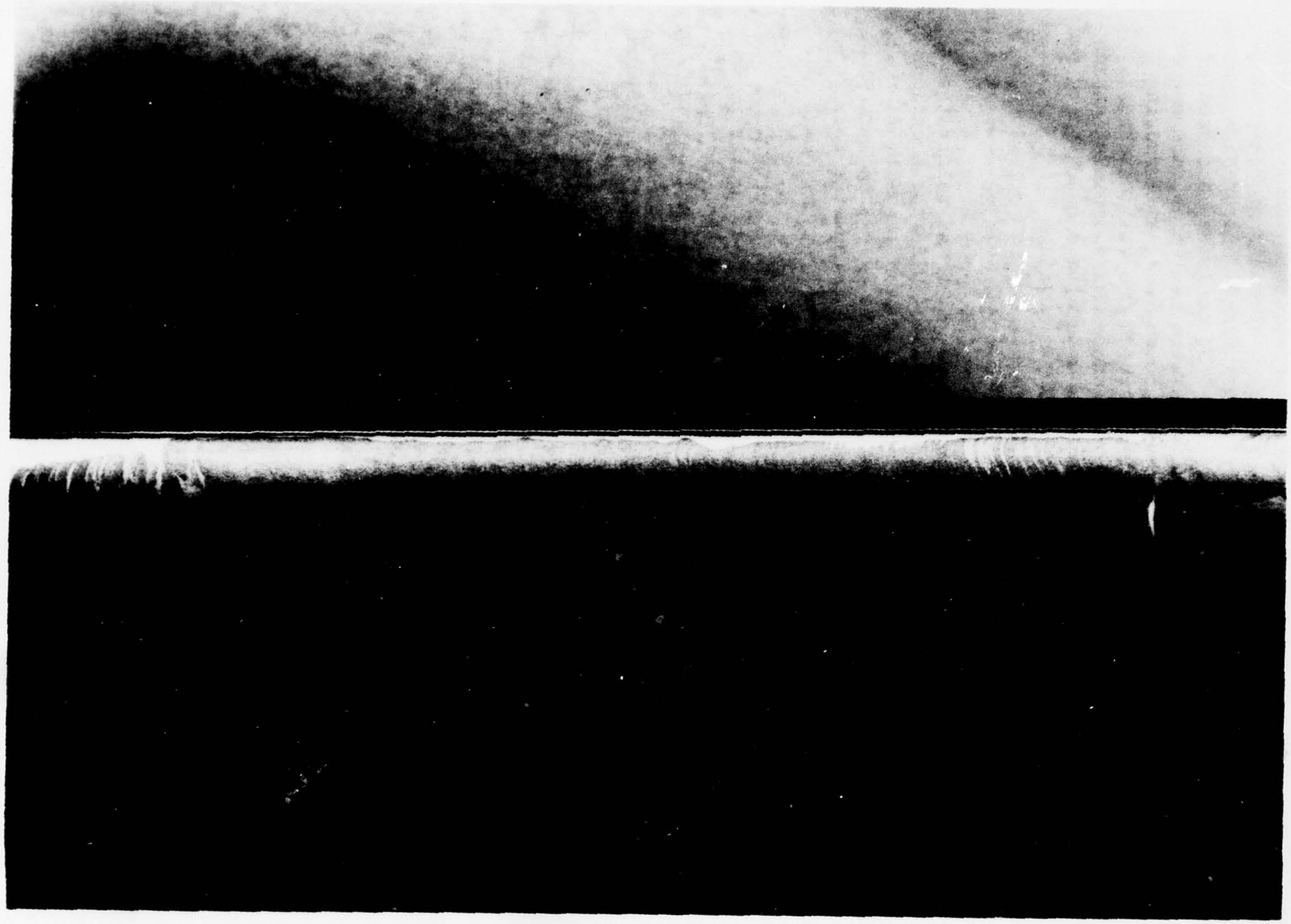


FIGURE 73. BLACK SMUT CONDITION OBSERVED ON EXTERNAL SURFACE OF SPAR TUBE S/N 7.

the gradual distribution of load from the spar to the attachment cuffs. After drilling the holes for the attachment cuffs, the internal diameter, ID of the holes were roller burnished. Prior to assembly of the attachment cuffs, the hardware for the internal pressurization detection system, blade inspection method, BIM, was installed. The hardware consisted of an access tube and two retension plates which were sealed at each end of the spar on the internal area. The spar is pressurized, and cracking induced by fatigue loading and propagating through the wall thickness causes a detectable loss in internal spar pressure. The titanium attachment cuffs were subsequently assembled and secured with through bolts and a paste adhesive.

7.1.2 Testing of Full-Scale Fatigue Specimens

Prior to fatigue testing the specimen was strain gaged and calibrated. Strain gaging was accomplished in general accordance with the locations specified on EWR 50000, Figure 72. Flatwise and edgewise calibration was accomplished by mounting the specimen as a cantilever I-Beam column and applying known moments with dead weights. Figure 74 shows the specimen during calibration.

Fatigue testing of the full-scale specimen was designed to determine fatigue crack initiation strength and failure modes. Testing was performed on a 200,000 pound pin-pin semi-resonate fatigue testing facility. A simulated centrifugal load of 50,000 pounds was mechanically applied by a soft spring loading mechanism which was attached through strain gaged and calibrated steel strips to the end of the specimen. The applied load produced 23,400 psi steady axial tension stress on the spar specimen. The spar was mechanically forced to vibrate slightly below its first mode edgewise natural frequency by a servo-controlled hydraulic actuator. The natural frequency was reduced by adding two, ten pound blade weights to the center of the specimen. The weights also assisted in obtaining the required maximum vibratory stresses at the center of the test specimen. The specimen was oriented in the test facility at an angle of 90° with respect to the plane of the support pins. The 90° angle was selected because it developed pure edgewise bending with maximum stress along the diffusion bond joint. Testing was conducted at a vibratory stress of $\pm$ 25,000 psi, a load level intended to demonstrate the adequacy of the CSDB joint. Figure 75 depicts the spar specimen in the fatigue facility.

7.1.3 Results of Full-Scale Fatigue Testing

After 145,000 cycles of testing at + 23,400 $\pm$ 25,000 psi, the specimen fractured thirty inches from one end (subsequently determined to be station 36). Prior to fracturing, the pressurized blade inspection system indicated a crack in the specimen. The crack was noted to be 3/4 inches in length. While the test was being oriented to obtain crack propagation data, fracture of the specimen occurred with no significant additional cycles. A good bending mement distribution was attained during fatigue testing. The bending moment distribution curve

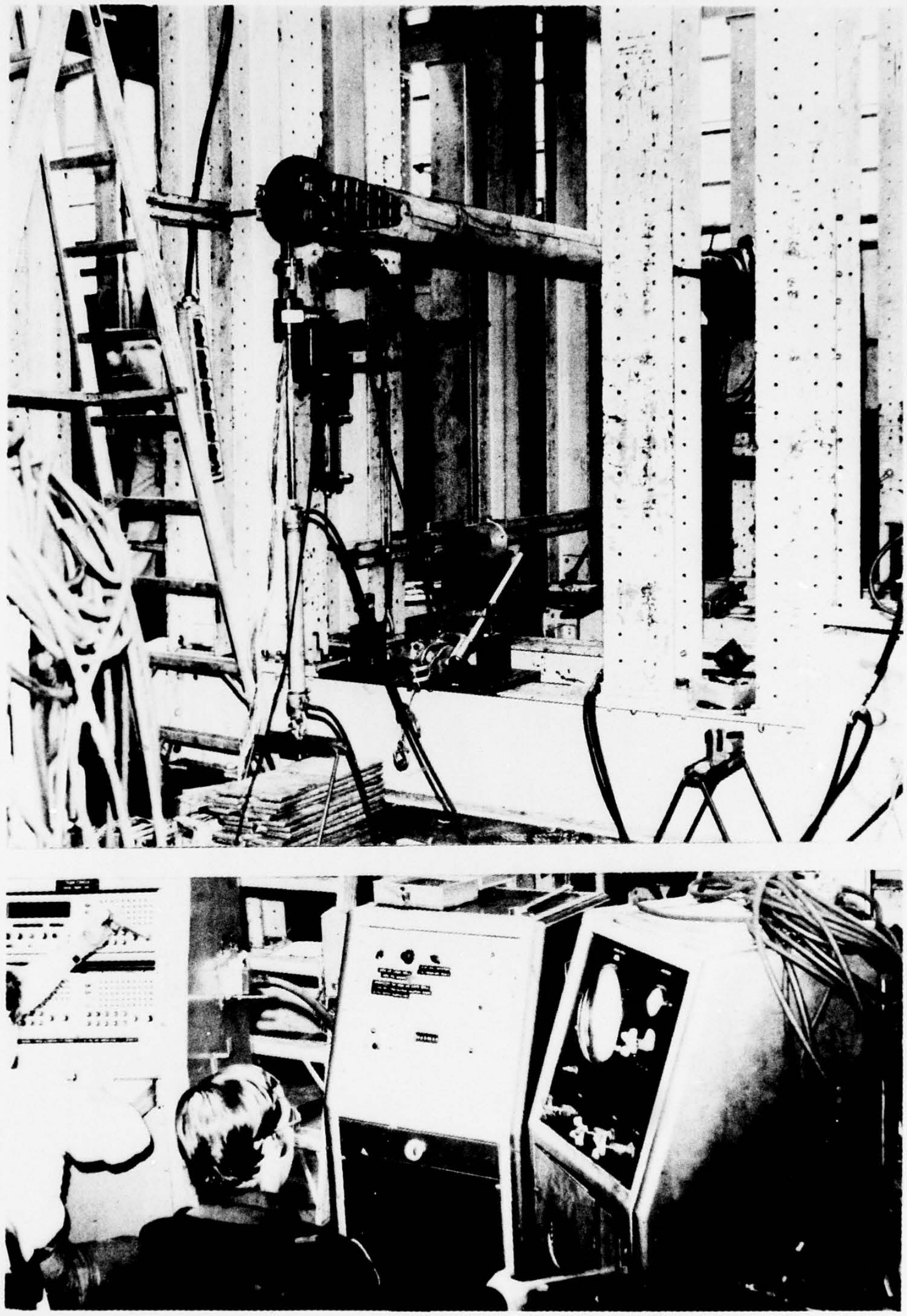


FIGURE 74. CALIBRATION SET-UP OF FULL-SCALE FATIGUE TEST SPECIMEN, S/N 7.

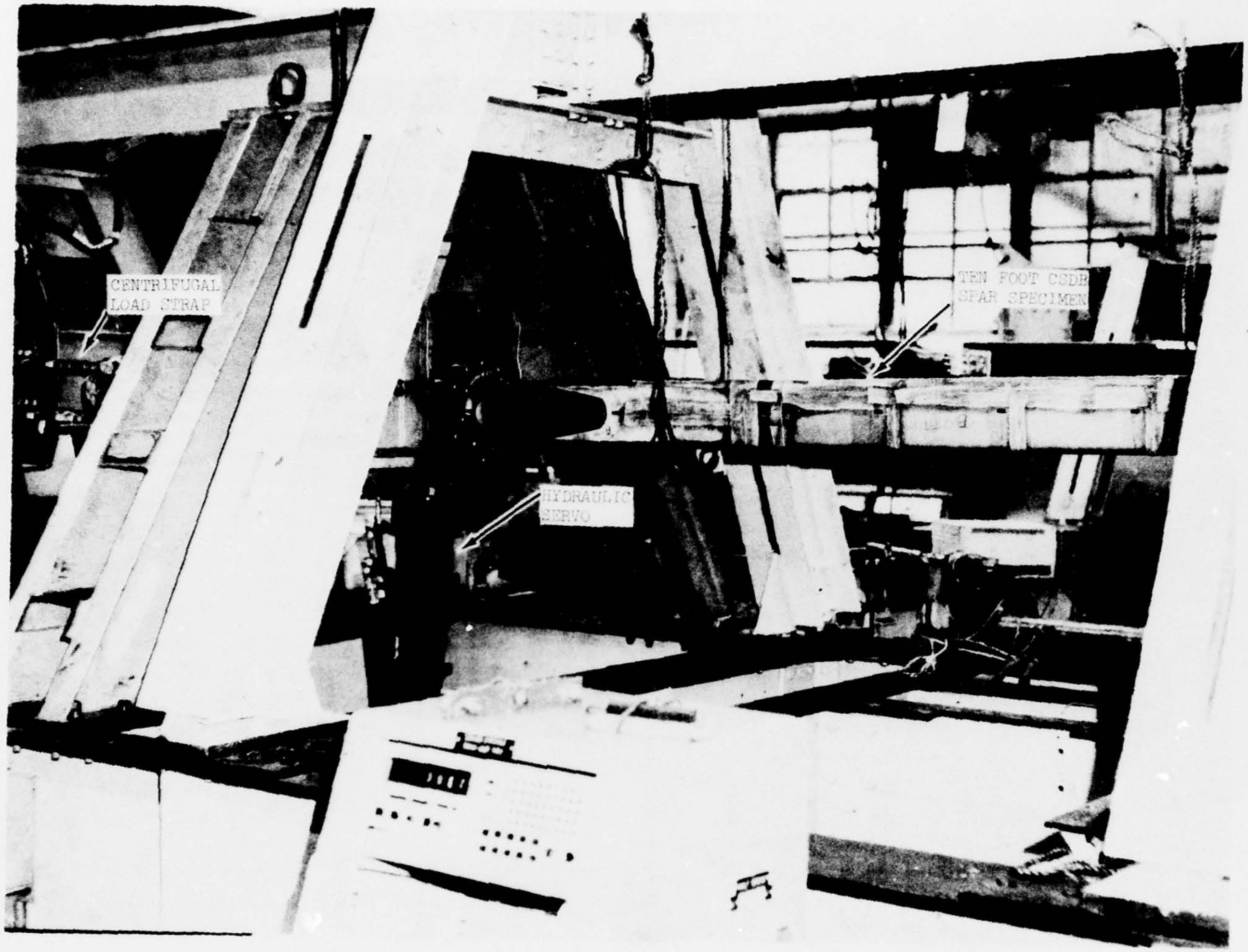


FIGURE 75. 200,000 POUND SEMI-RESONANT FATIGUE TEST FACILITY WITH TEN FOOT FULL SCALE BLACK HAWK SPAR S/N 7 INSTALLED.

is depicted in Figure 76. Visual inspection of the separated specimen showed that the fracture was located one inch inboard from the end of the tapered fiberglass laminates, reference Figure 77. Cracking was noted to have initiated perpendicularly to the diffusion bond joint, and across the localized anomaly previously observed on the internal surface of the specimen. No evidence of span wise or longitudinal separation of the diffusion bond joint was detected. The diffusion bond did not rupture along the longitudinal axis of the spar specimen as the circumferential crack approached and propagated transversely across the bond joint. Previous experience has shown that longitudinal rupturing may occur along the bond joint when transverse or chordwise crack propagation reaches a diffusion bond joint of poor bond quality. Results of the full-scale fatigue test are shown in Figure 78. The results indicate that CSDB blade spars are structurally adequate for use in UH-60A BLACK HAWK main rotor blades.

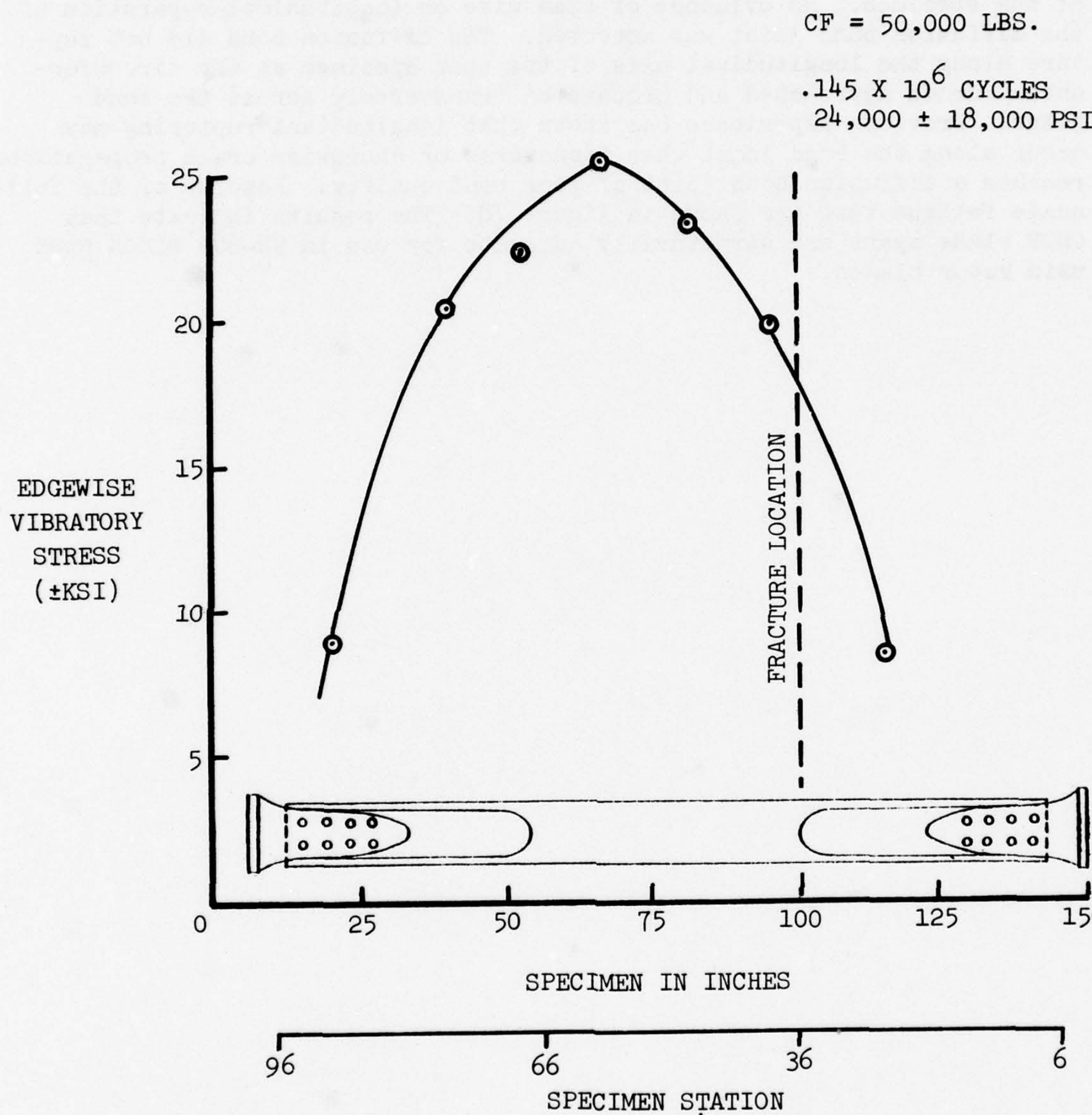
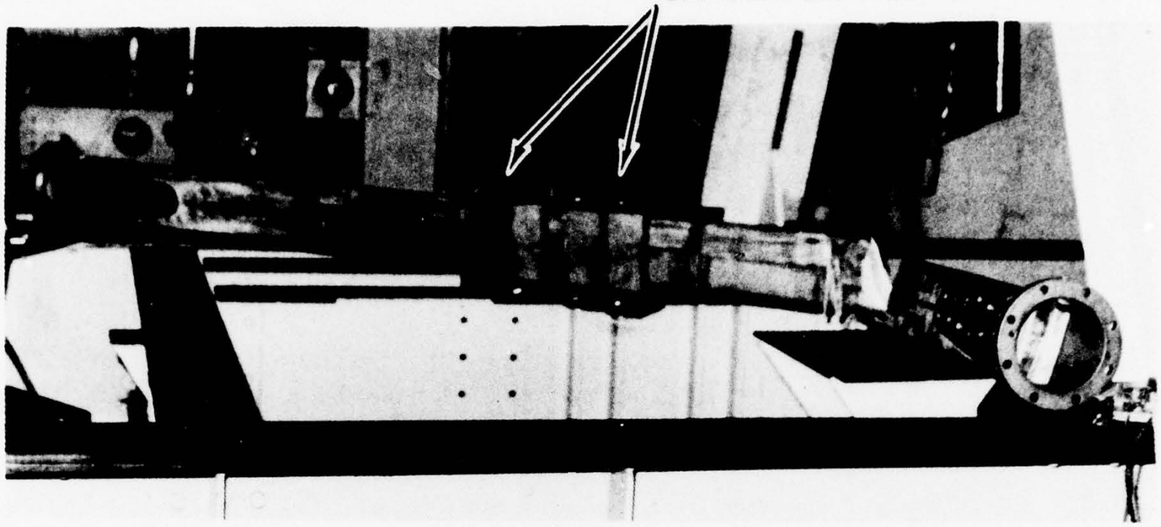


FIGURE 76. EDGEWISE BENDING MOMENT DISTRIBUTION CURVE.

TWO TEN POUND WEIGHTS



OVERALL

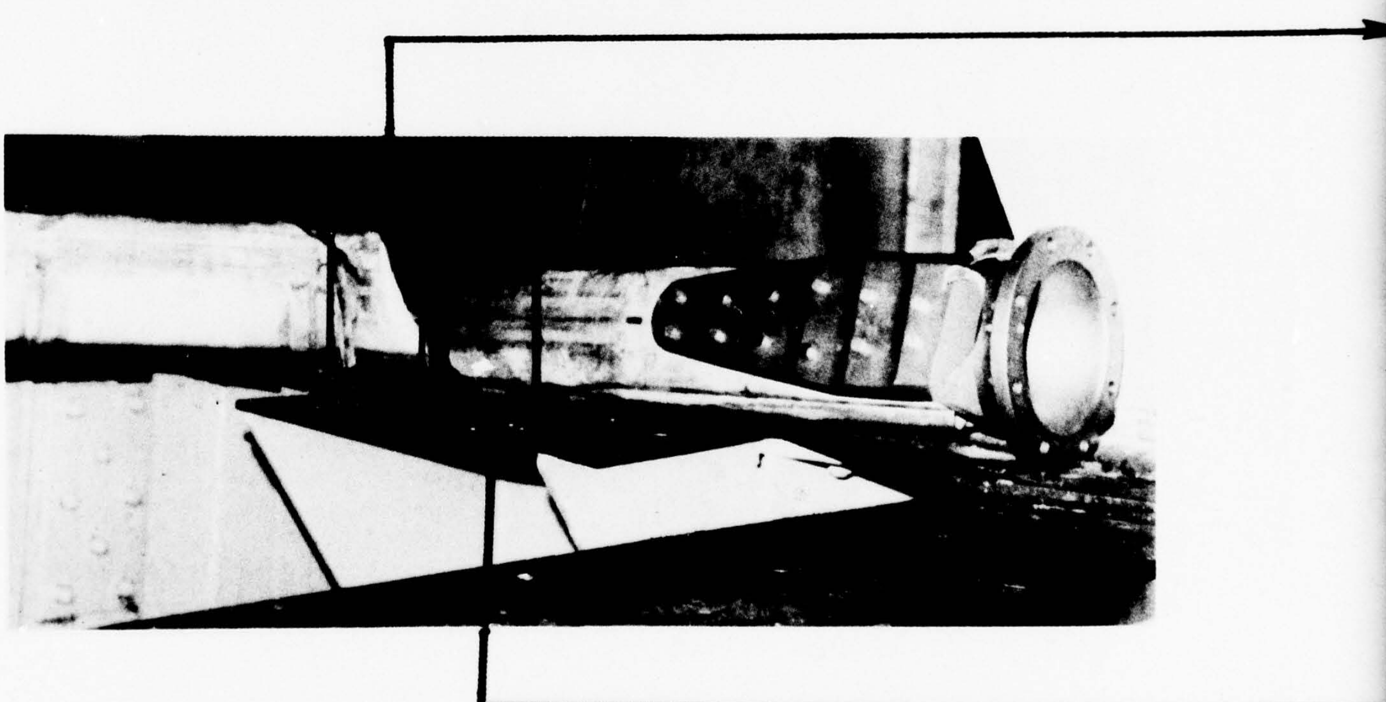
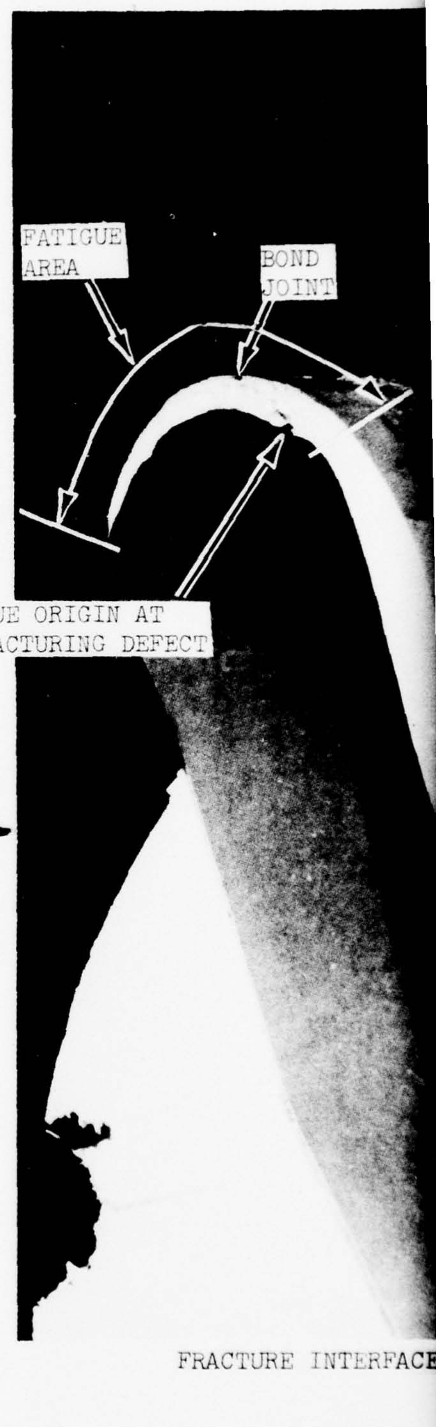


FIGURE 77. FRACTURED TEN-FOOT CSDB BLACK HAWK SPAR FATIGUE SPECIMEN, S/N 7.

FRACTURE INTERFACE - LEFT SIDE



FRACTURE INTERFACE

2

FACE - RIGHT SIDE

7.1.4 Failure Analysis of Full-Scale Fatigue Specimen

In order to ascertain the cause and mode of cracking of the full-scale spar specimen, visual, fractographic, and metallographic examination were performed. Visual inspection disclosed that the specimen separated approximately 30 inches, station 36 from the start end of the spar specimen and that the fatigue origin emanated from a manufacturing defect located on the internal surface of the specimen. Review of the specimen's x-ray film showed that the manufacturing defect was the linear abnormality detected previously during non-destructive inspection, and described in subsection 6.1 and depicted in Figure 59. Examination of the fracture interface confirmed the mode of cracking to be fatigue originating at a linear interaction abnormality on the internal surface of the specimen away from the diffusion bond joint. The cracking was noted to have propagated bidirectionally in a transverse or chordwise mode, perpendicular to the diffusion bond joint with a typical elliptical propagation pattern. The abnormality was observed to be approximately 1/8 inches in diameter extending through 1/3 of the wall thickness at the fracture location. Fatigue propagation of the crack extended through the wall thickness to the external surface of the specimen and was approximately 1-1/2 inches in length before complete separation of the specimen occurred due to static overload. Cyclic loading propagation was approximately 10% of the spar's cross section; the remaining 90% was overload. The origin in the manufacturing defect, at the metal flow region, was located away from the diffusion bond joint on the internal surface of the spar. In conjunction with the applied stresses, the manufacturing defect produced a stress concentration that was sufficient to initiate fatigue cracking. The applied stresses at the crack location were 70 to 75% of maximum stress on the spar specimen reference stress distribution curve, Figure 76. Figure 79 is a view of the separated specimen and cross section of the fracture interface, depicting the origin, fracture texture, and extent of the anomaly. Optical and dye-penetrant spot check examination of the bond at the fracture regions revealed no evidence of longitudinal joint separation. That is, the diffusion bond did not rupture along the longitudinal axis of the spar specimen as the circumferential crack approached and propagated transversely across the bond joint. Previous experience has shown that longitudinal rupturing along the diffusion bond joint occurs when transverse crack propagation reaches a diffusion bond joint of poor bond quality, reference (a). Macro-examination of a transverse section through the bond depicted a well defined 1-1/4 inch heat effected zone with no manifestation of a bondline. Micro-examination of the heat effected zone and base metal disclosed no finite bondline, only a coarse large transformed beta grain structure in the heat effected zone and surrounding alpha-beta structure typically observed in this sheet material, reference Figure 80.

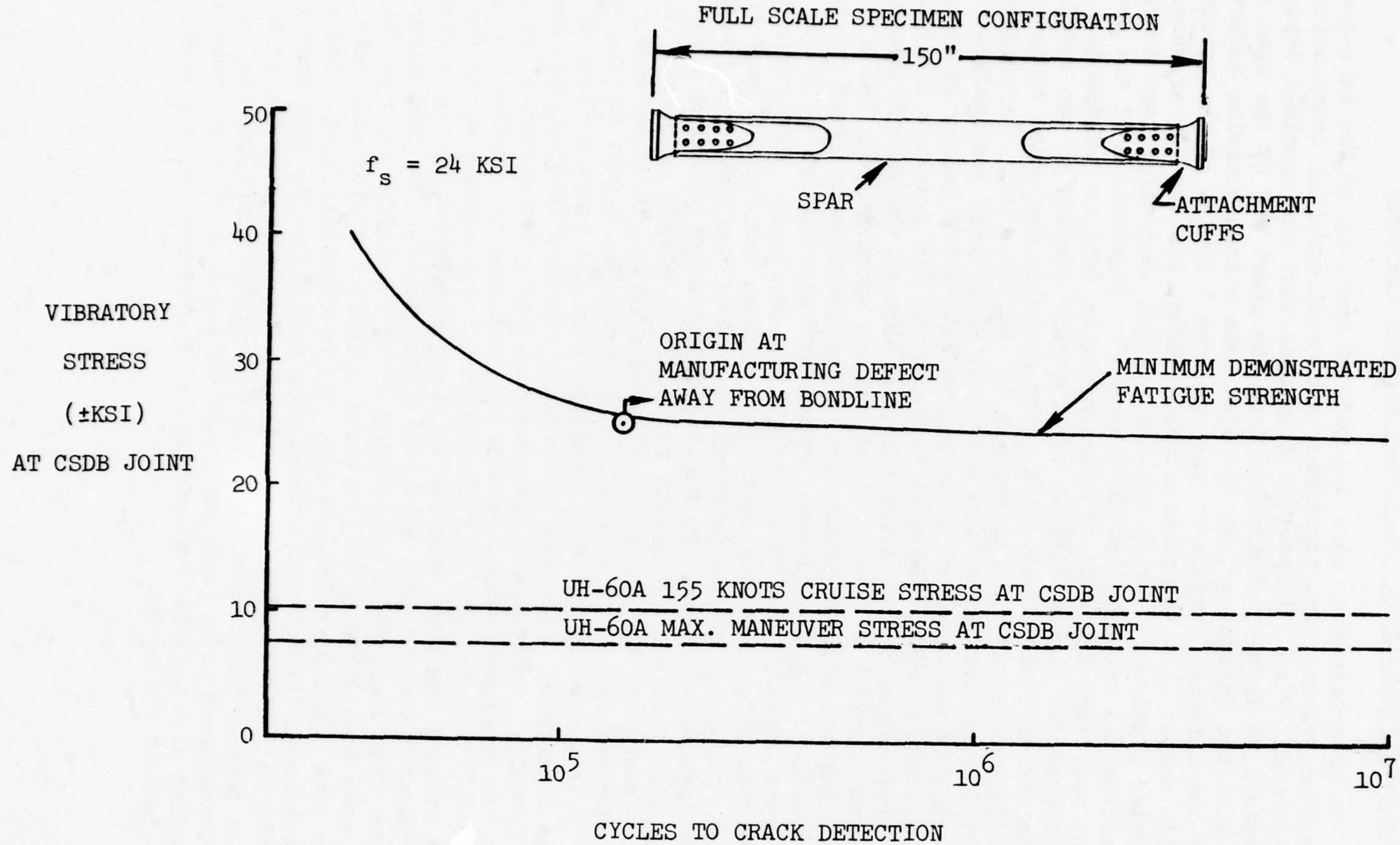
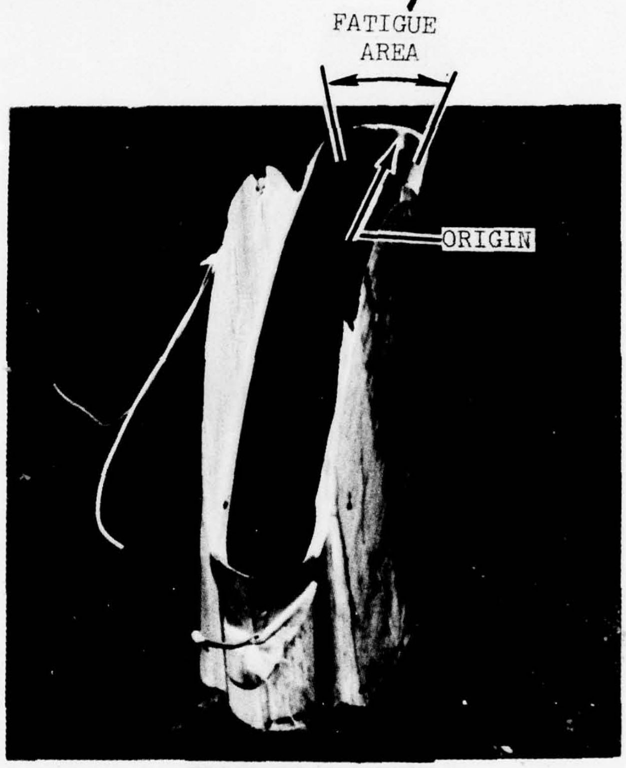


FIGURE 78. FATIGUE TEST RESULTS OF FULL SCALE TEN FOOT LONG BLACK HAWK CSDB SPAR S/N 7.

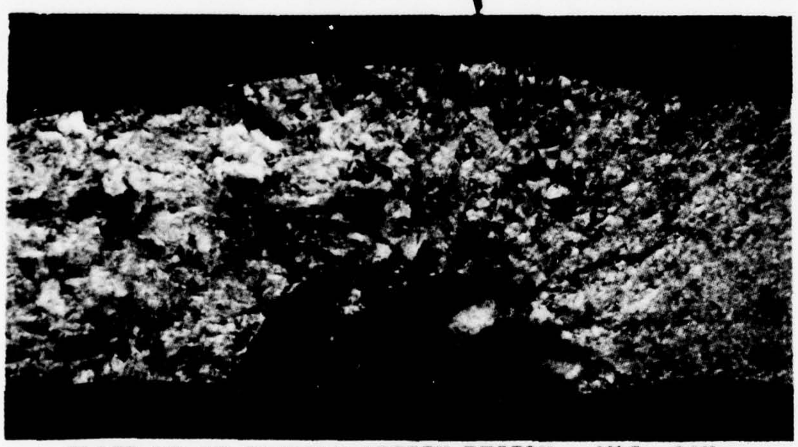
FRACTURE AREA



FRACTURE SURFACE

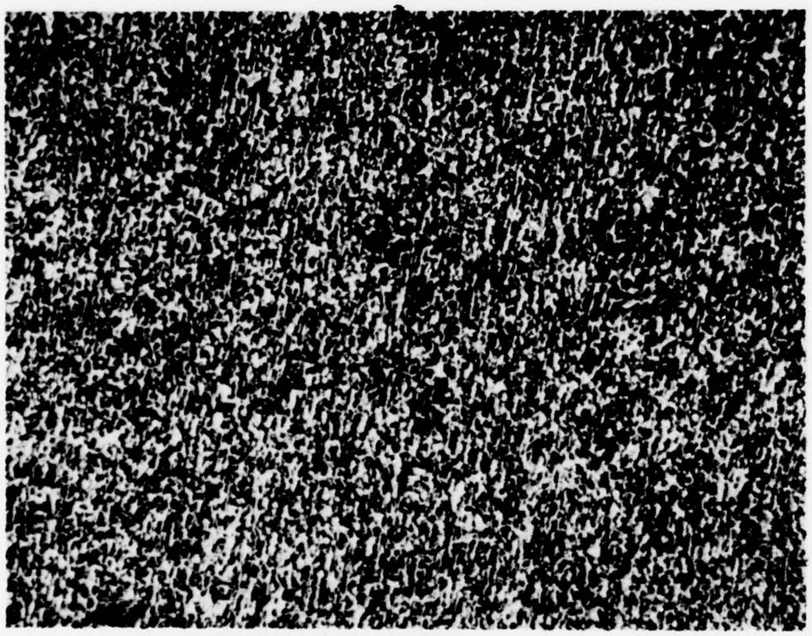
FIGURE 79. FRACTURE AREA OF CSDB FATIGUE TEST SPECIMEN, S/N 7 DEPICTING ORIGIN AT INTERACTION CONDITION ON INTERNAL SURFACE.

TIGUE AREA.
TE ORIGIN AT ANOMALY ON INTERNAL SURFACE.



CLOSE-UP OF FATIGUE ORIGIN REGION. MAG. 10X.
NOTE ANOMALY EXTENDING THROUGH 1/3 OF WALL
THICKNESS AND GRANULAR TEXTURE OF FRACTURE
SURFACE.

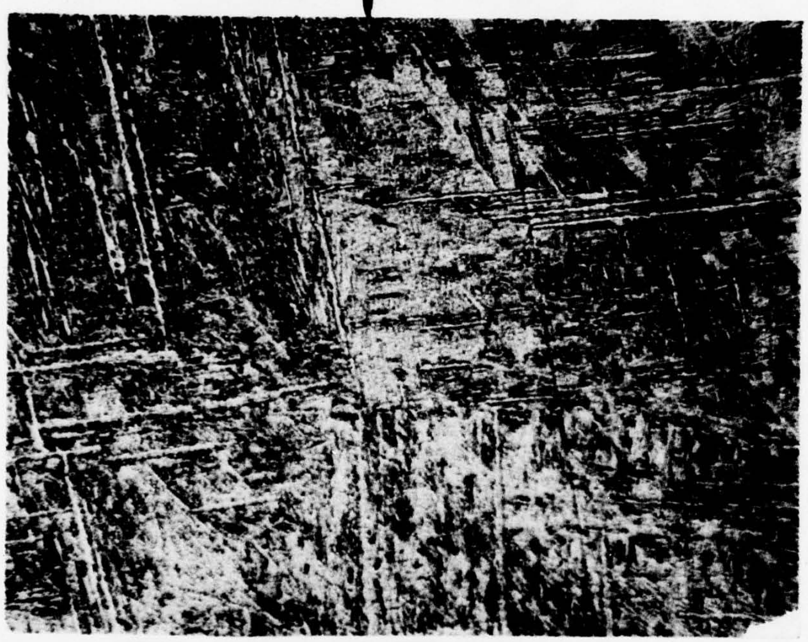
WELL DEFINED HEAT AFFECT
NO MANIFESTATION OF BOND



TYPICAL BASE METAL
ALPHA BETA STRUCTURE 200X

FIGURE 80. TRANSVERSE SECTION THROUGH BOND AREA CSDB FATIGUE TEST SPECIMEN S/N 7, ILLUSTRATING TYPICAL STRUCTURE.

FECTED ZONE
BONDLINE 2X



CENTER OF HEAT AFFECTED ZONE
COARSE LARGE β GRAIN STRUCTURE 200X

1

2

7.2 Small-Scale CSDB Titanium Specimens

Twelve small-scale test specimens were fabricated from spar tube S/N 8 and fatigue tested. Results of the testing show that diffusion bonding produces satisfactory joint quality, well above flight load requirements for the spar application.

7.2.1 Preparation and Fabrication of Small-Scale Fatigue Specimens

After completion of the non-destructive inspection methods, spar tube S/N 8 was cut into segments and small-scale fatigue specimens were fabricated and subsequently tested. Selection of the location for machining of the small-scale fatigue test specimens from spar tube S/N 8 and sectioning of the spar tube into twelve specimen blanks was accomplished as depicted in Figure 81. After sectioning, the specimen blanks were cleaned and Turko coated in preparation for the simulated hot forming cycle. In order to prevent any warpage during the simulated hot forming cycle, the small-scale specimens were held between alternate layers of titanium and steel plates. Three "C" clamps, one at each end and one in the center, were used to mechanically hold the specimens to a base plate. The clamped stackup was placed in a furnace, heated to 1335°F ± 35°F and held at temperature for five hours. After the five hour cycle, the heat was shut off and the clamped specimens were allowed to cool overnight in the furnace with the door closed. Upon removal of the clamped specimens from the furnace, the clamps were removed and the specimens were placed in hot Kolene salt solution to remove the oxide scale and inert film. Subsequently, the specimens were acid etched in nitric hydrofluoric removing .001 to .002 inches of material from each surface to eliminate any minute layer of alpha case that could have formed during the simulated hot form operation. The twelve small-scale specimens were final machined into the test specimen configuration depicted in Figure 82. The final machined small-scale specimens were polished in the reduced area of the thickness dimension prior to shot peening. Shot peening was performed in accordance with the spar drawing requirements of 330 size shot to an intensity of .008 to .012 Arc height.

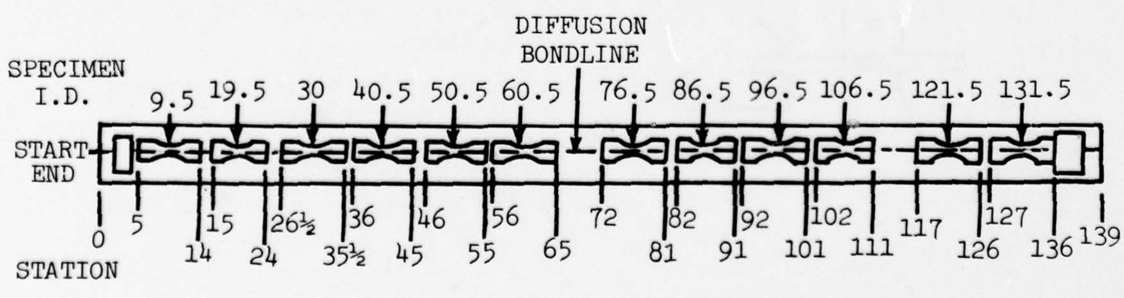


FIGURE 81. LOCATION OF SMALL-SCALE FATIGUE SPECIMENS AS RELATED TO CONTINUOUS SEAM DIFFUSION BONDED SPAR TUBE S/N 8.

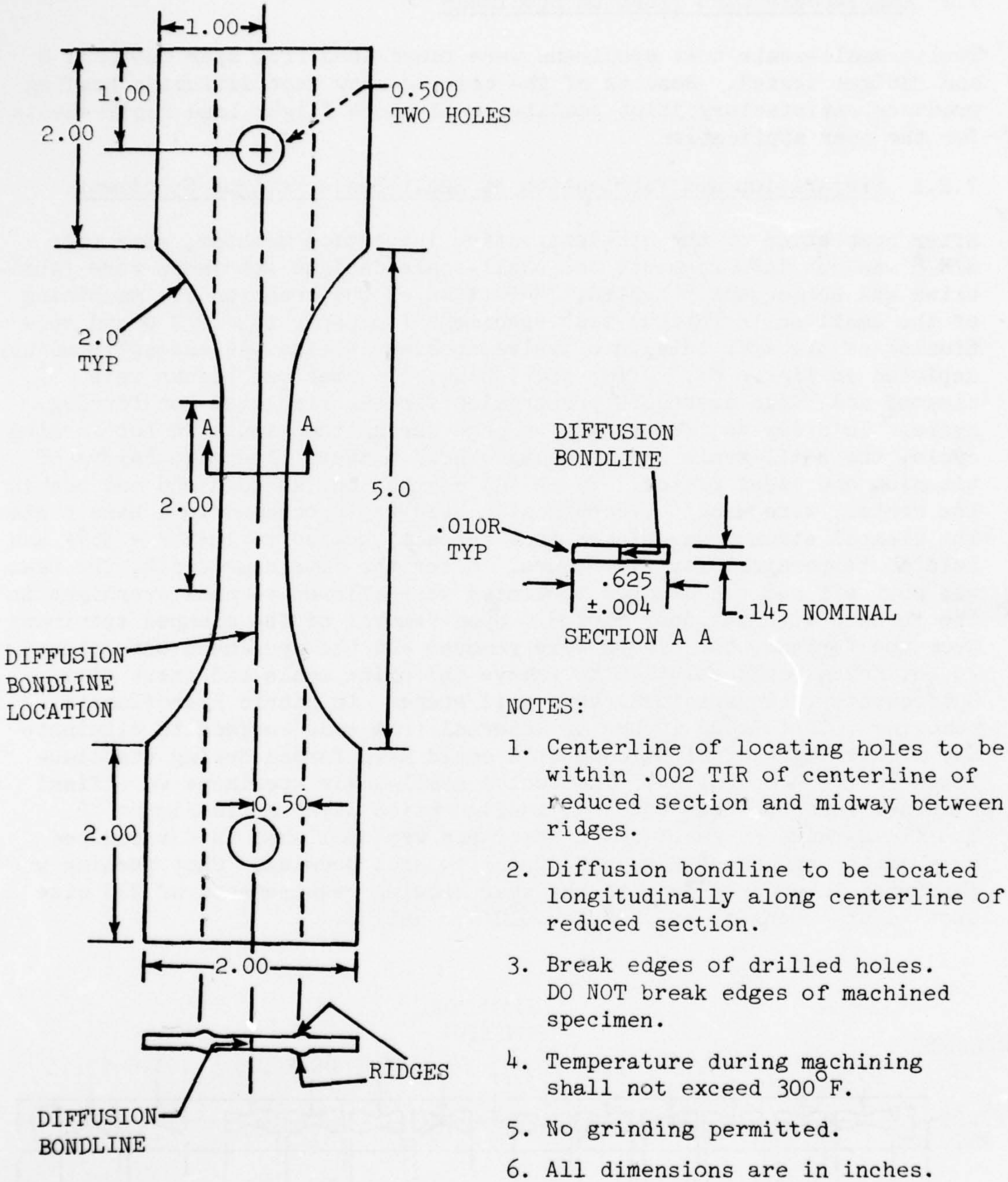


FIGURE 82. SMALL-SCALE FATIGUE TEST SPECIMEN CONTINUOUS SEAM DIFFUSION BOND.

7.2.2 Testing of Small-Scale Fatigue Specimens

Fatigue testing was performed at room temperature under Axial Load on Sonntag SF-1-U Universal Fatigue Testing Machine equipped with 5:1 load amplifiers as shown in Figure 83. Twelve small-scale specimens fabricated from spar tube S/N 8 were tested. Rigid grips retained the specimen under tension-tension loading. A typical test specimen installed in the grips is shown in Figure 84. Loads were applied at 60 cycles per seconds, H_z and were measured by a calibrated full bridge load cell in series with the test specimen. The static and dynamic load cell output were read with the aid of an Ellis BA-12 Bridge Amplifier and Oscilloscope Console. All specimens were tested at a ratio of minimum to maximum stress, R of 0.1.

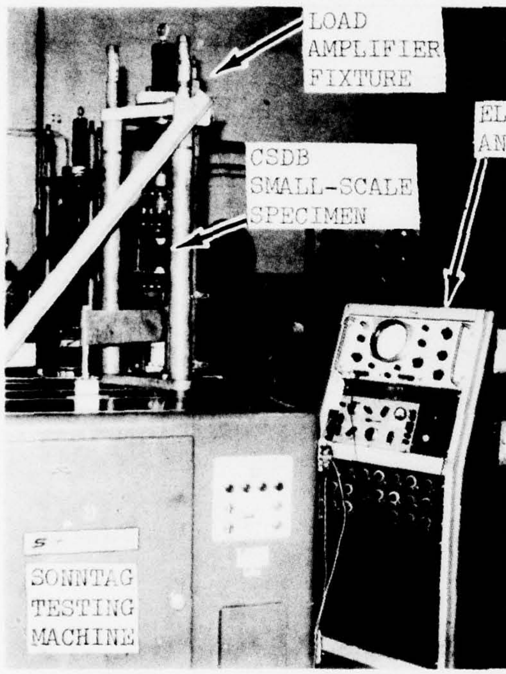


FIGURE 83. **SMALL-SCALE FATIGUE** TEST FACILITY.

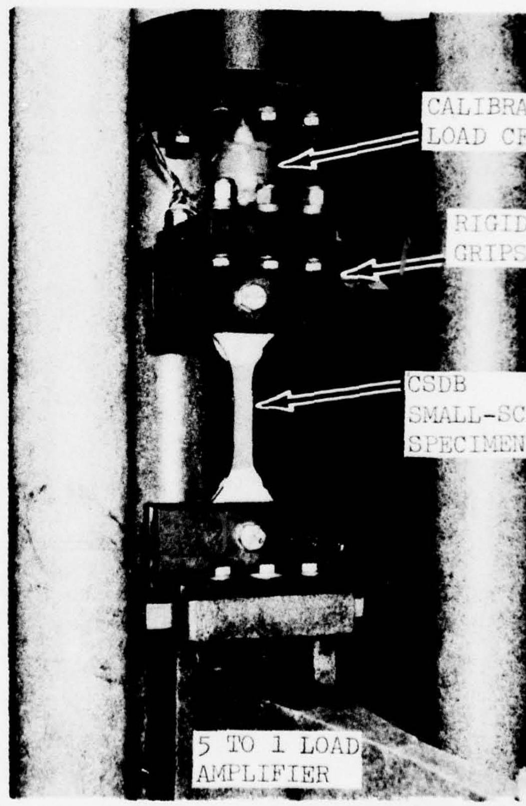


FIGURE 84. **CLOSE-UP OF SMALL-SCALE FATIGUE** SPECIMEN ARRANGEMENT.

7.2.3 Results of Small-Scale Fatigue Specimen

Results of fatigue testing are tabulated in Table V and plotted in Figure 85. The mean curve for the specimens tested is well above the equivalent cruise flight and maximum measured maneuver condition on the BLACK HAWK aircraft.

TABLE V

SUMMARY OF FATIGUE TEST RESULTS
CSDB SPAR TUBE S/N 8 SMALL-SCALE SPECIMENS

SPECIMEN IDENTIFICATION (S/N) *	MAX. STRESS (KSI) (R=0.1)	CYCLES TO FRACTURE (1×10^6)
9.5	70	.091
19.5	70	2.733
30.0	80	1.387
40.5	100	.045
50.5	80	.158
60.5	100	.101
76.5	80	.091
86.5	80	.091
96.5	80	1.268
106.5	80	.778
121.5	80	2.095
131.5	70	9.344

* S/N corresponds to specimen location along length of tube spar S/N 8.

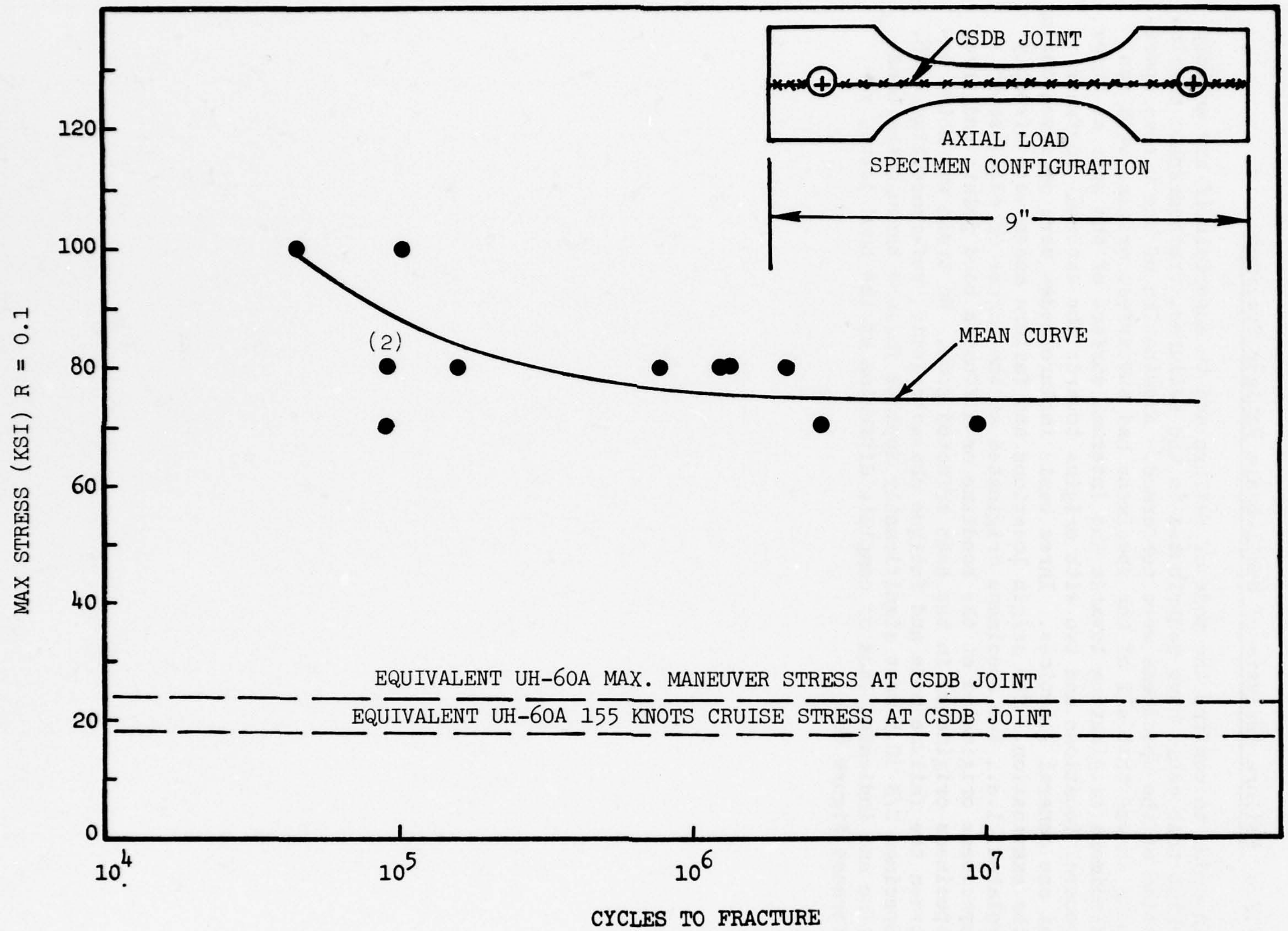


FIGURE 85. FATIGUE TEST RESULTS FOR CSDB SMALL SCALE SPECIMENS.

7.2.4 Failure Analysis of Small-Scale Fatigue Specimen

In order to confirm the mode of failure and to ascertain if any anomaly exist that could have contributed to the failures, fractographic examination of the specimens were performed. Examination of the twelve specimens showed that all of the specimens had subsurface origins with ten specimens originating towards the internal surface of the spar at three general locations and two with origins towards the external surfaces at one general locations. Three basic failure modes were observed during the examination. The origin locations and failure modes were directly related, i.e., two specimens originated at the corner or edge; seven specimens originated at the bondline or diffusion bond joint; and three specimens originated in the heat effected zone. No trend was noted between the failure mode and fatigue characteristic, reference Figure 86. Specimen S/N 50.5 most significantly depicts failure through the bondline and indicated lack of complete diffusion at the bond joint, reference Figure 86.

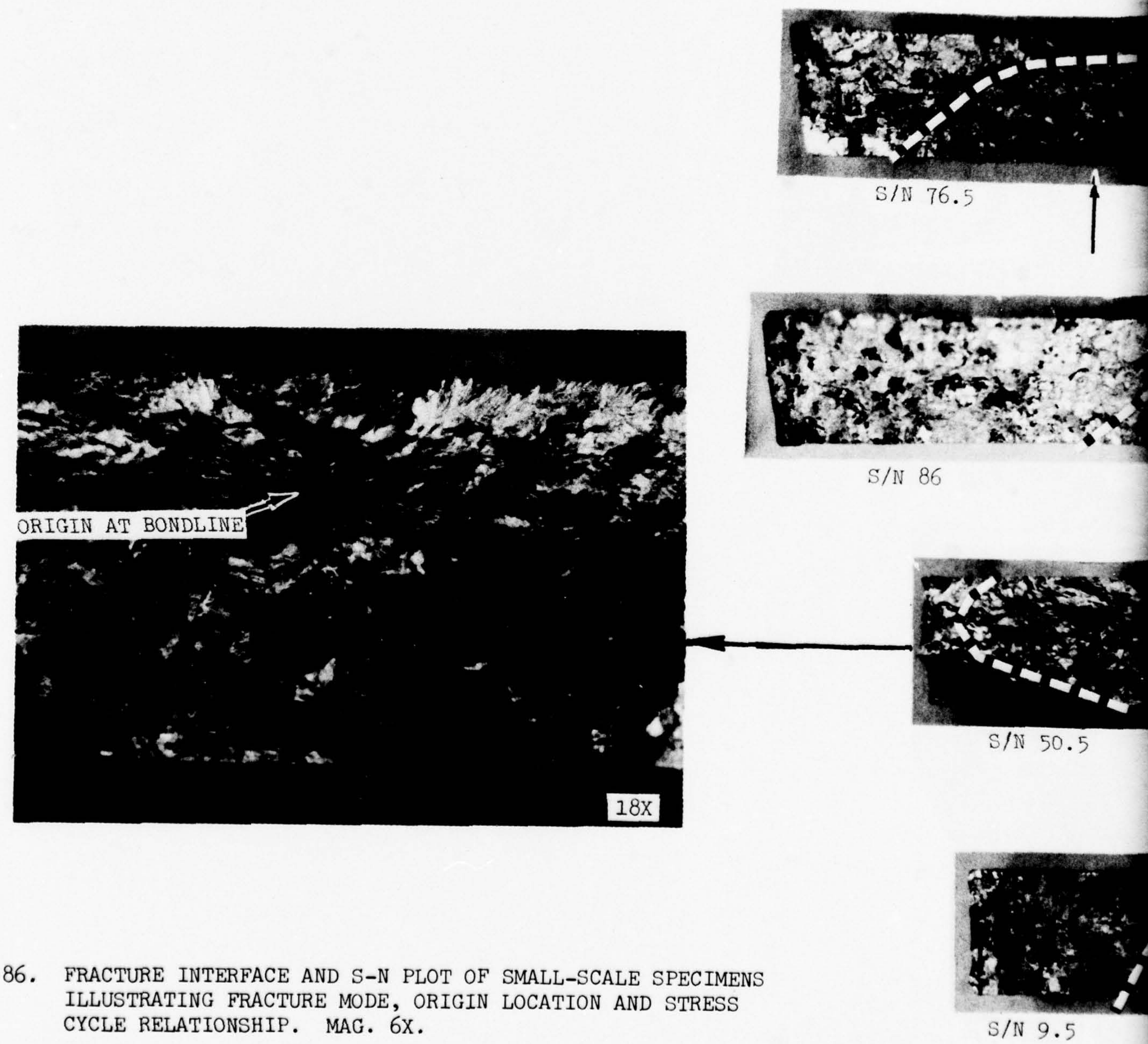
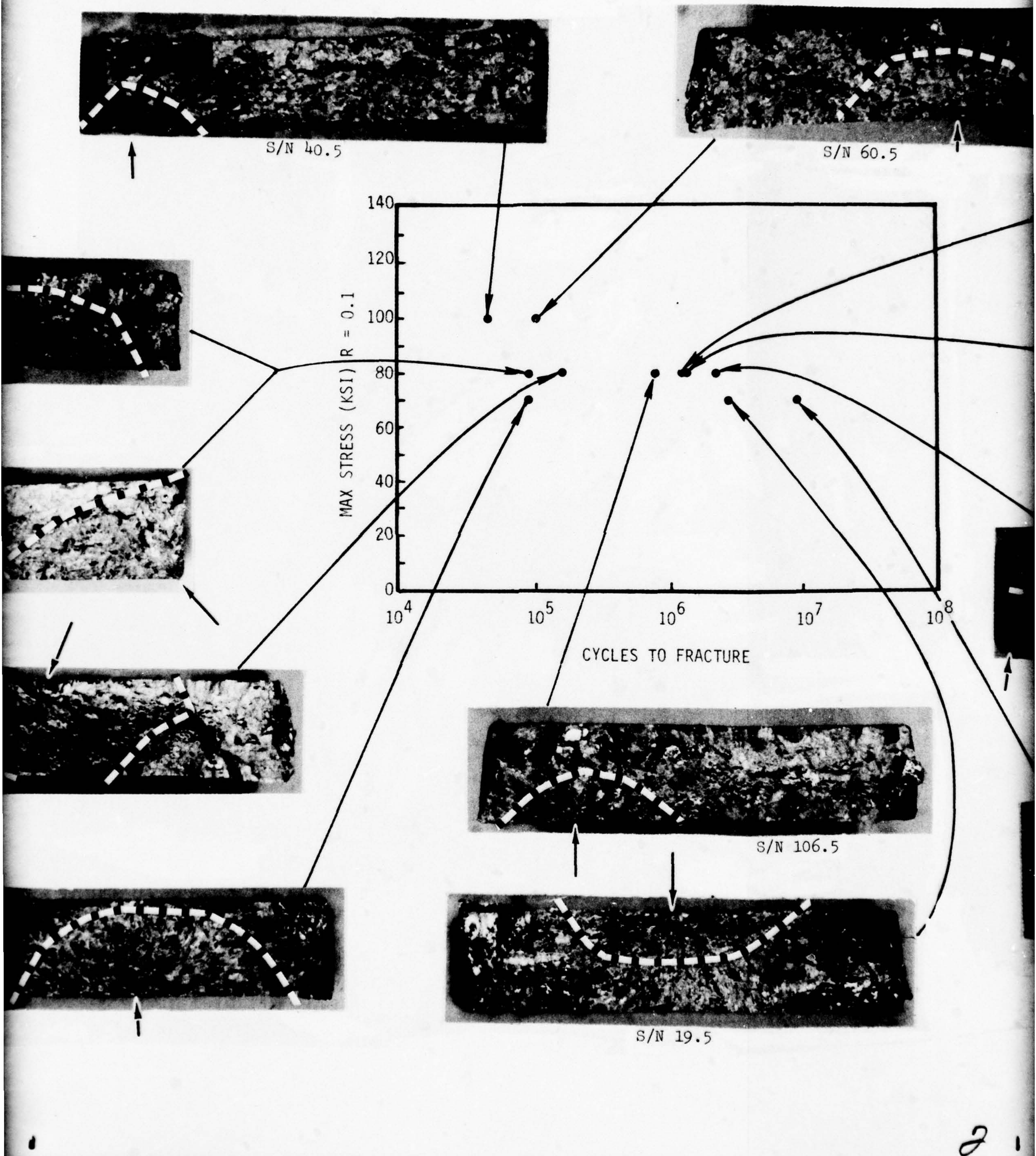


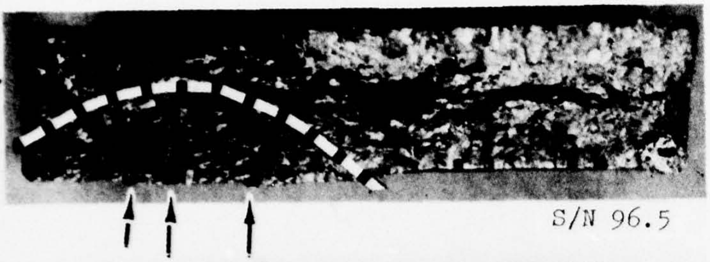
FIGURE 86. FRACTURE INTERFACE AND S-N PLOT OF SMALL-SCALE SPECIMENS ILLUSTRATING FRACTURE MODE, ORIGIN LOCATION AND STRESS CYCLE RELATIONSHIP. MAG. 6X.



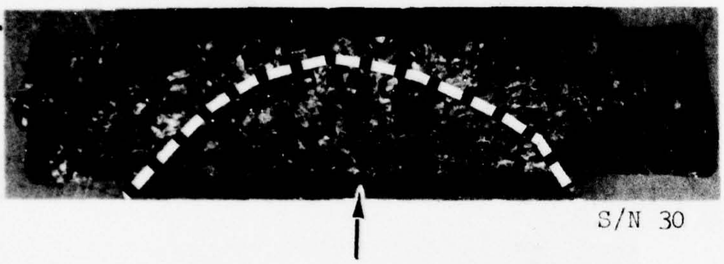
S/N 40.5
S/N 60.5
140
120
100
80
60
40
20
0
MAX STRESS (KSI) R = 0.1
10^4
10^5
10^6
10^7
10^8
CYCLES TO FRACTURE
S/N 106.5
S/N 19.5

NOTE:

1. FATIGUE AREA DEPICTED BY DASH LINE.
2. ARROW INDICATES FATIGUE ORIGIN.



S/N 96.5



S/N 30

S/N 121

S/N 131.5

7.3 Fatigue Testing of D-Spar Specimen, S/N 2-A

A CSDB D-spar, S/N 2-A which was originally fabricated and fatigue tested under a previous CSDB program, DAAG46-72-C-0175 as reported in Reference (a), was retested in this program. The purpose of the retesting was an attempt to collect additional fatigue test data. Testing of the subject specimen resulted in fracture of the specimen at the first set of attachment bolt holes, similar to the fracture experienced in the previous program. No significant additional fatigue test data was obtained in the retesting activity. The fracture through the attachment bolts was attributed to high stresses at the bolt end attachments. These high stresses were due to a poor spanwise stress distribution associated with the shortness of the specimen and the mass of the end attachment cuffs.

7.3.1 Fabrication and Testing of D-Spar Fatigue Specimen

A 9 foot long CSDB D-spar, S/N 2-A, fabricated and fatigue tested in a previous program, Reference (a), was retested in this program by shortening the spar to 8 feet. The purpose of the retesting was to obtain additional fatigue data for evaluation of the CSDB concept applied to helicopter rotor blade spar fabrication with a minimum investment. Retesting of the D-spar was possible because during initial testing of this D-spar, fracture occurred seven inches from one end, through the outboard attachment bolt holes, leaving sufficient length of spar for possible testing of a short specimen. The fractured end of the original 9 foot D-spar was removed one inch from the inboard bolt hole. New glass-epoxy and stainless steel laminates and wide titanium clevis cuffs were installed as attachment ends. The overall length of the spar was 110.25 inches from cuff-to-cuff face. This is the same successful fabrication technique used on D-spar S/N 1-A in the previous program and reported in Reference (a), Figure 87 is a view of the fabricated short fatigue test specimen prior to testing. The present laminate buildup on spar S/N 2-A was thicker than used in the initial testing of this spar. The greater laminate buildup produces a stiffer attachment end condition which reduces the stresses at the bolt holes and attempts to force failure to occur in the more highly stressed central region of the spar. The specimen was instrumented with strain gages, top and bottom, to form a bridge which would denote the edgewise bending of the specimen, and on top to depict the total stress along the diffusion bond. A sketch of the specimen with strain gages installed is illustrated in Figure 88. The specimen was calibrated for edgewise testing and was installed in a 200,000 pound semi-resonant fatigue test facility as shown in Figure 89. The 200,000 pound semi-resonant fatigue test system is equipped with a hydraulic motor and servo capable of applying both the required centrifugal and vibratory forces. The hydraulic servo excites the spar near first mode resonance and the amplitude is adjusted in an attempt to achieve the desired vibratory stress at the mid-point of the specimen. Specimen strain output was monitored using an Ellis dynamic strain console

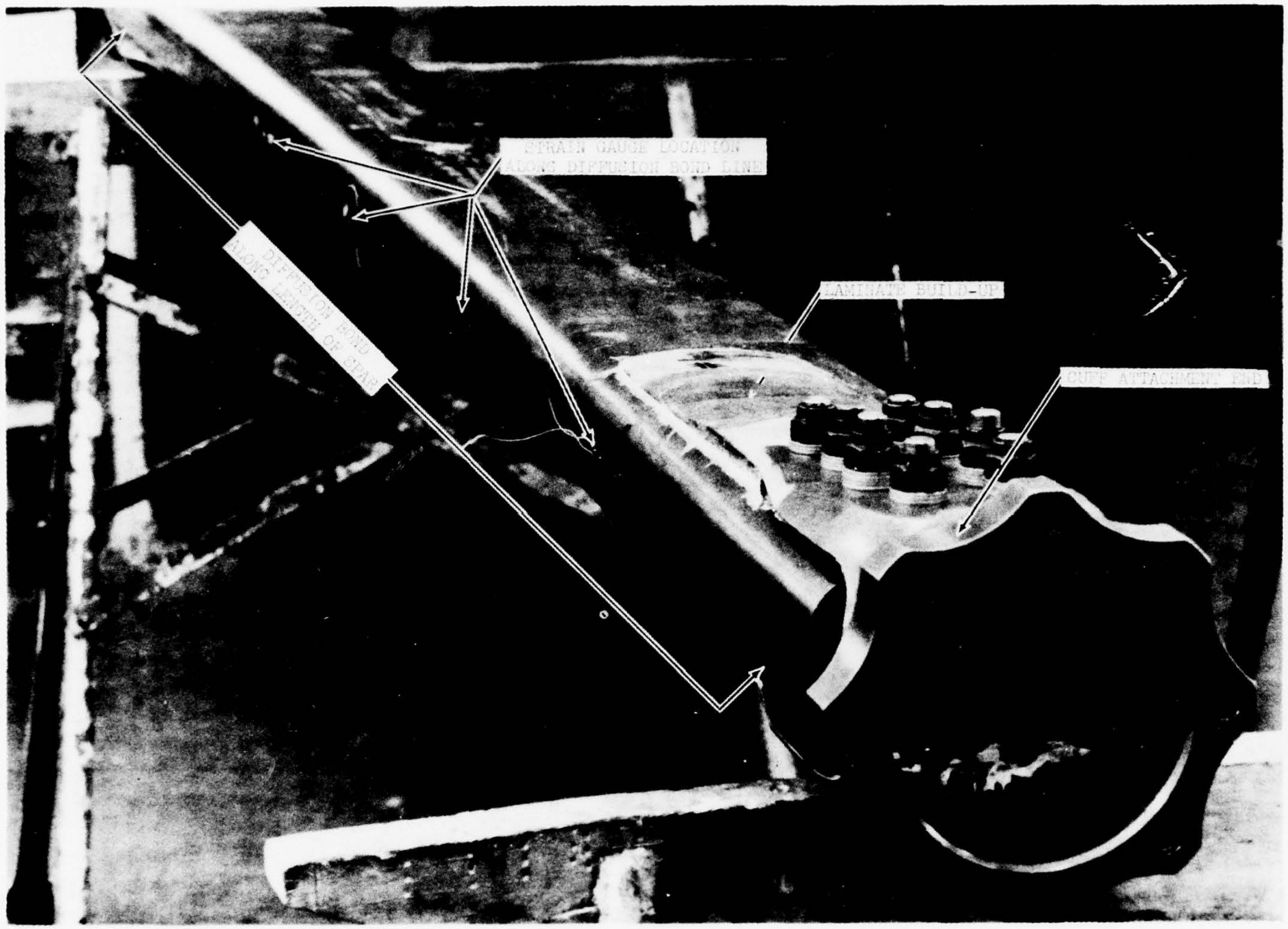


FIGURE 87. D-SPAR FATIGUE TEST SPECIMEN S/N 2-A.

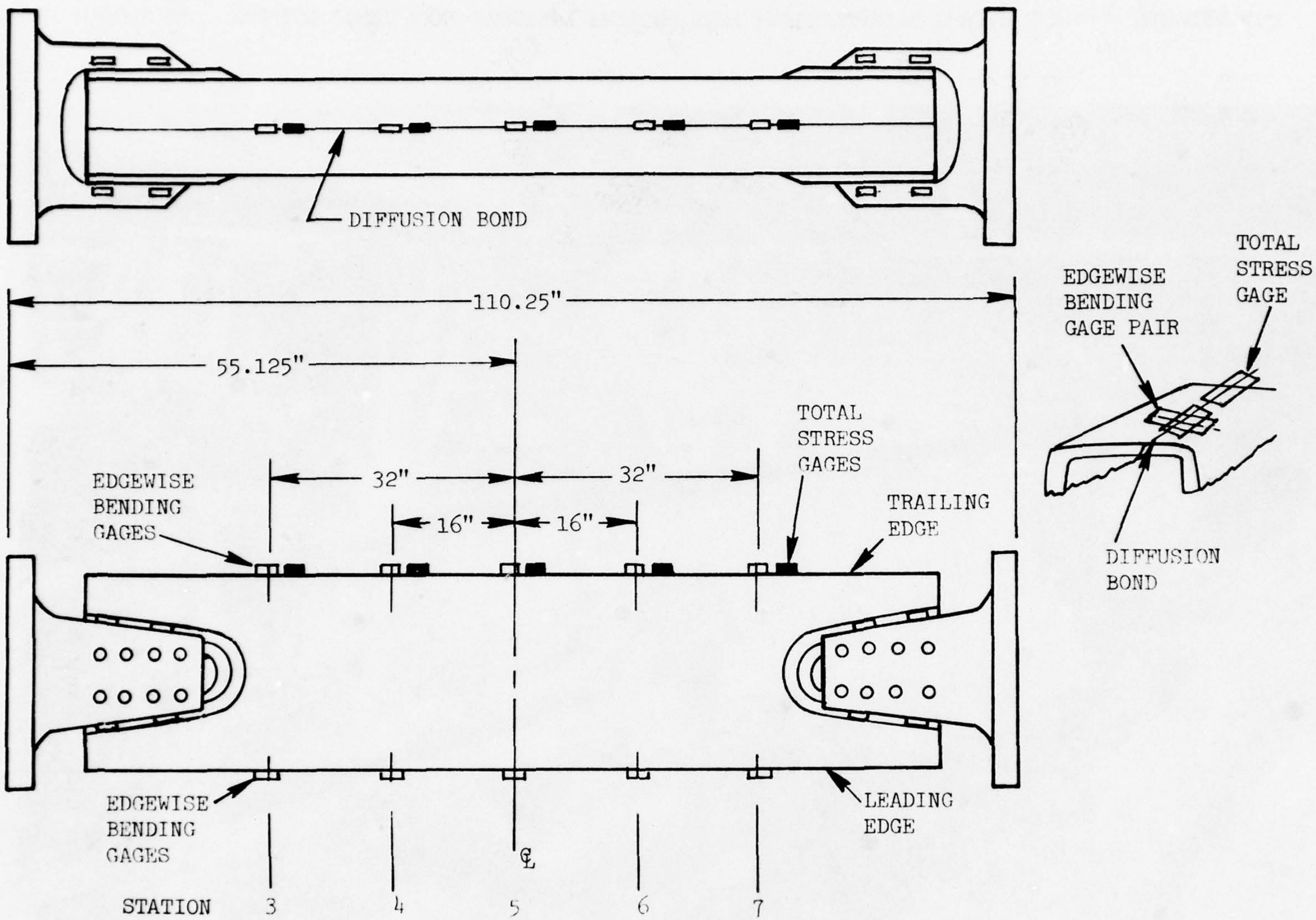


FIGURE 88. STRAIN GAGE DIAGRAM, CSDB TITANIUM D-SPAR, EIGHT FOOT SPECIMEN, S/N 2A.

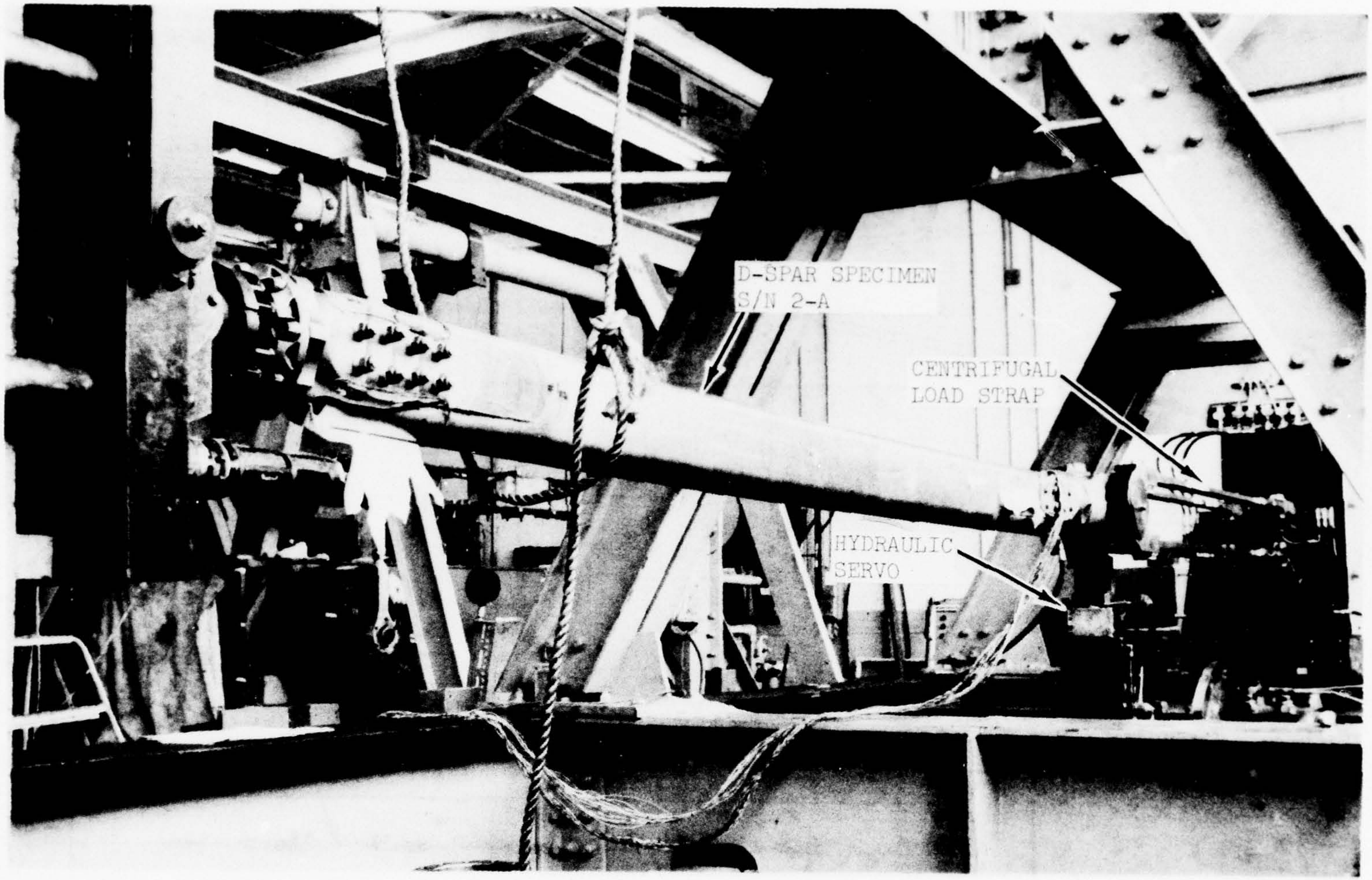


FIGURE 89. 200,000 POUND SEMI-RESONANT FATIGUE TEST FACILITY WITH D-SPAR S/N 2-A INSTALLED.

and oscilloscope. Figure 63 depicts the instrumentation used in the testing. A pressurized blade inspection system was the prime crack detection method.

7.3.2 Results of D-Spar Fatigue Specimen

While attempting to obtain the desired stress distribution, the D-spar ruptured after 181,000 cycles of testing. Fracture occurred through the first set of attachment bolt holes as shown in Figure 90. Rupturing of the D-spar was not associated with the diffusion bond joint. Although the short specimen had experienced 181,000 cycles of fatigue testing, no significant fatigue test data was obtained from this testing. The lack of significant fatigue test data is related to the low stress obtained during testing. That is, the edgewise bending stress at the midpoint of the short specimen had not reached the desired testing load of ± 25,000 psi before the specimen ruptured. Table VI lists the vibratory stresses and respective cycles obtain during testing. A stress distribution curve from the initial load survey was obtained and indicates that the spar midpoint was not the point of maximum stress, Reference Figure 91. The higher stresses in this specimen were developed at the outboard (excited) end where the failure occurred. This poor distribution is attributed to the shortness of the specimen and the mass of the end attachment fittings.

TABLE VI

SUMMARY OF FATIGUE TEST RESULTS OF D-SPAR RETEST

Applied Centrifugal Force (lbs)	Steady Stress (PSI)	Approximate Vibratory Bending Stress at D-spar Midpoint ($\pm$ KSI)	Estimated Cycles 1×10^6
37,000	28,000	7	.071
37,000	28,000	14	.089
37,000	28,000	18	.007
37,000	28,000	20	.007
37,000	28,000	22	.007
		Total Cycles	.181

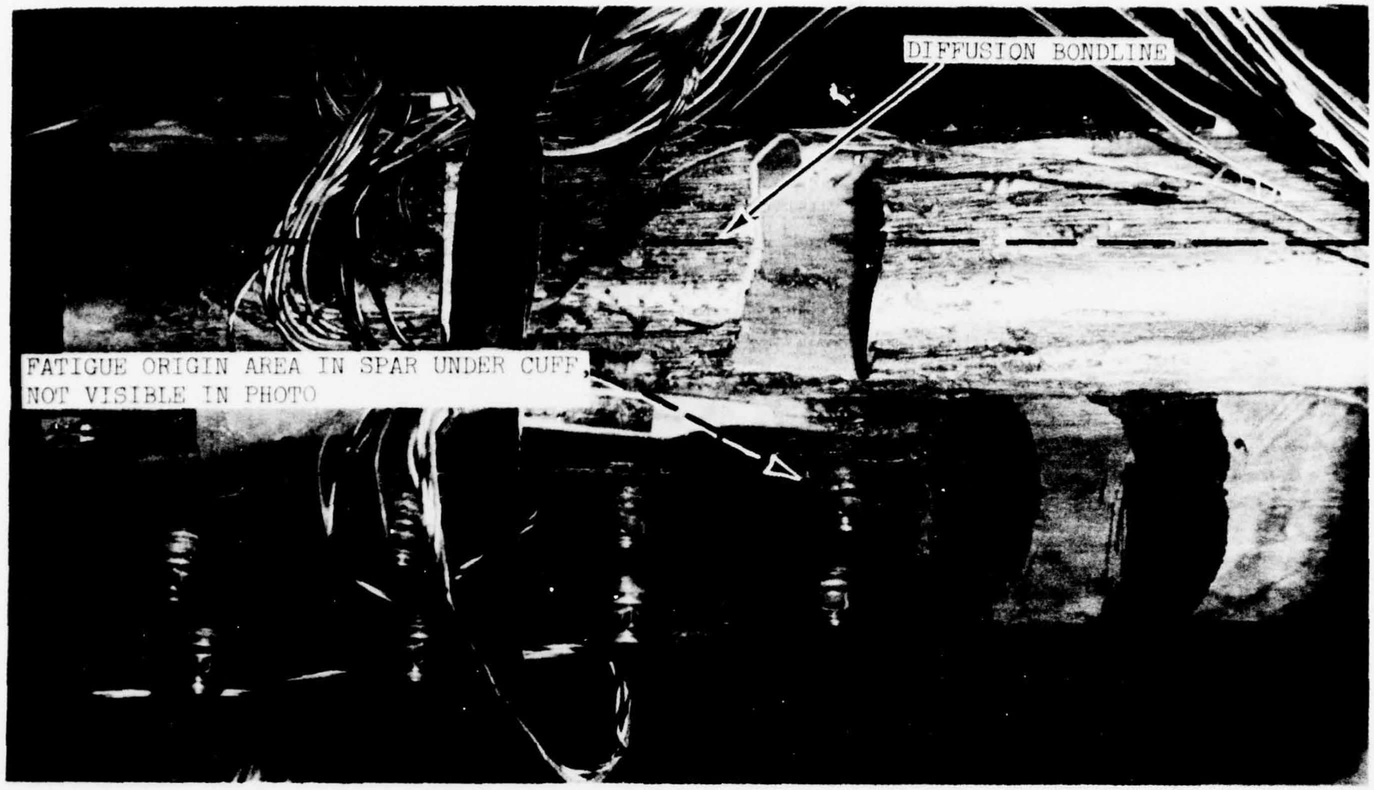


FIGURE 90. FRACTURE AREA, FATIGUE TEST SPECIMEN S/N 2-A.

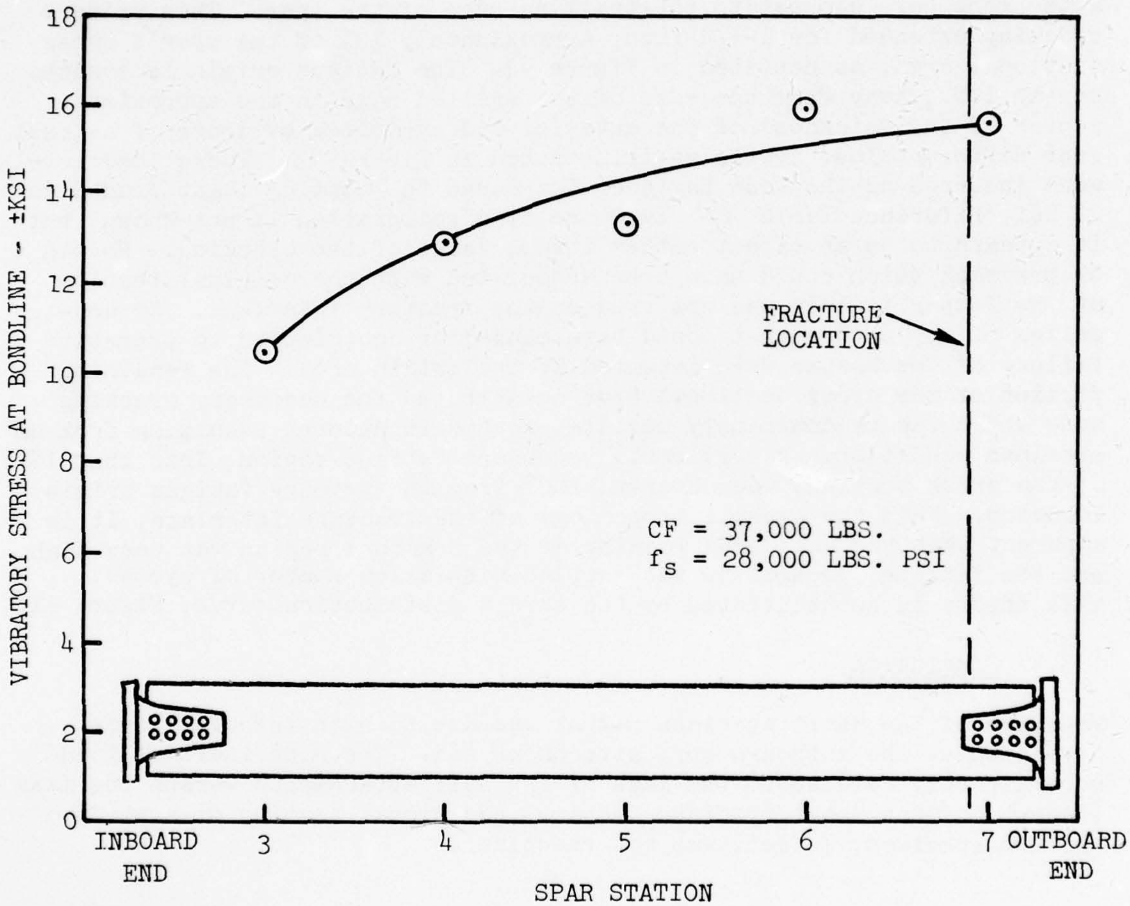


FIGURE 91. TYPICAL STRESS DISTRIBUTION, DIFFUSION BONDED D-SPAR S/N 2-A OBTAINED DURING SETUP.

7.3.3 Failure Analysis of D-Spar Fatigue Specimen

In order to confirm the cause of failure and to establish the mode of cracking, visual, fractographic, and metallographic examinations were performed. Inspection of the ruptured spar showed the failure had occurred through the first set of attachment holes at one of the attachment cuffs. Examination of the fracture interfaces disclosed them to manifest two basic modes of crack propagation. The initial or primary mode of cracking was brittle, cyclic type propagation, fatigue in nature with the origin emanating from the inner diameter, I.D. of the outboard attachment hole closest to the trailing edge of the spar. This primary cracking extended for 1-1/2 inch, approximately 10% of the spar's cross sectional area, as depicted in Figure 92. The fatigue origin is located on the I.D., away from the edge of the drilled hole in the approximate center of the thickness of the material and exhibited evidence of a least four different load levels as illustrated in Figure 93. These load levels were incurred as the Test Engineer increased the testing loads from 0 to 22 ksi, Reference Table V. Evidence of discoloration is not known, but it appears to be an effect rather than a cause of the cracking. No old or precrack which could have been associated with the original testing of the D-spar in 1974 was observed on the fracture interface. No anomalies of any nature that could have caused or contributed to premature failure of the D-spar were detected at the origin area. The remaining portion of the cross sectional area constituted the secondary cracking mode which was predominately ductile, static in nature, resulting from an overload condition. A very small secondard fatigue region, less than 1% of the cross section, was observed 180° from the primary fatigue origin location. From the overall morphology of the fracture interface, it is apparent that the unit area loading at the fracture region was very high and the fatigue propagation was rappied with a low number of cycles. This theory is substantiated by the stress distribution curve, Figure 91.

7.3.4 Conclusion

Fracture of the short specimen D-spar was due to high inertial loads developed at the outboard cuff attachment end. The high inertial loads were directly related to the mass of the cuff attachments versus the mass (length) of the short specimen D-spar. Additional testing of a stiff shorter specimen, 7 feet, was not practical.

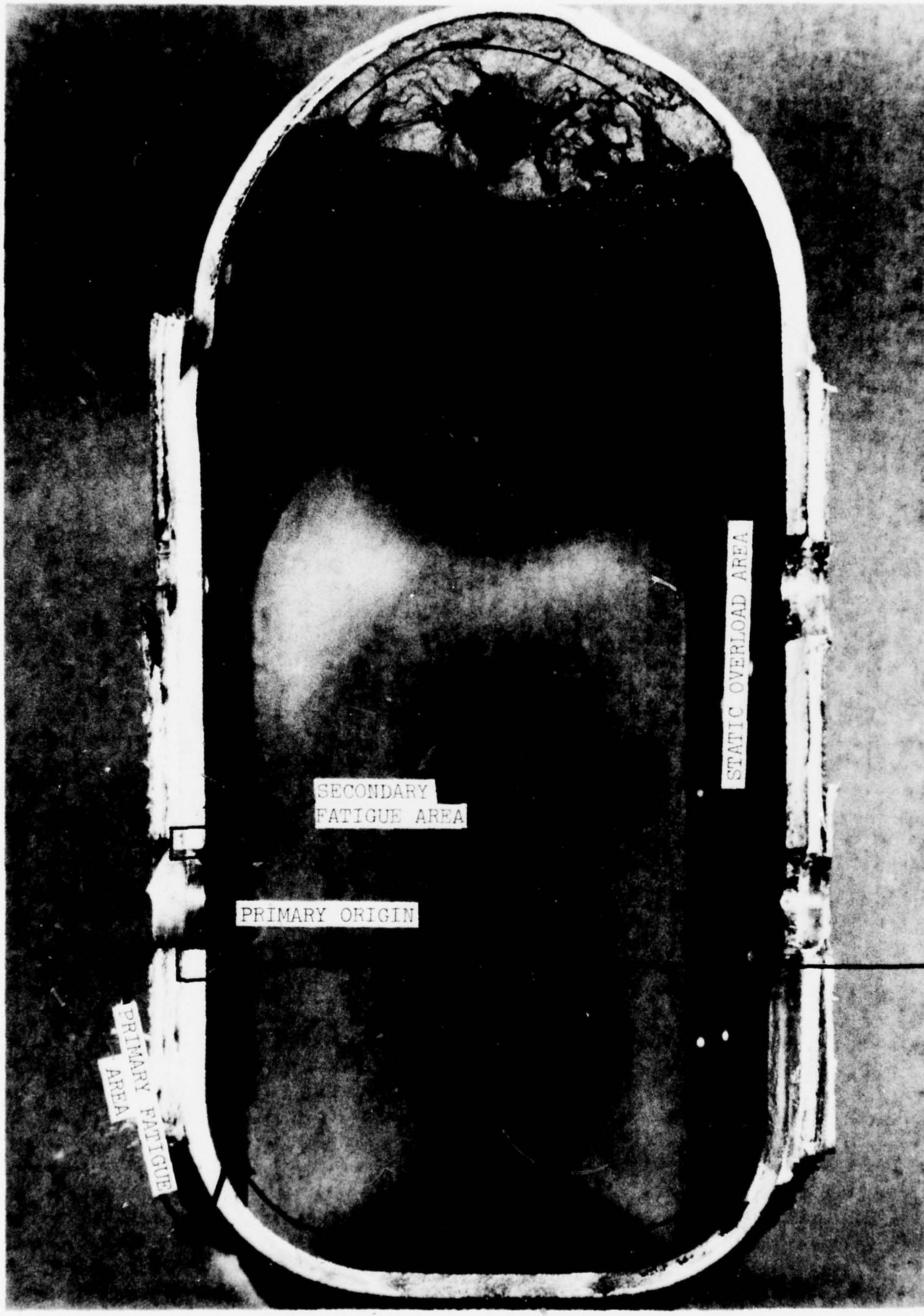


FIGURE 92. FRACTURE INTERFACE WITH TWO DISTINCT FRACTURE MODES.

FIGURE 93. CLOSE-UP OF ORIGIN AREA.
(NOTE INDICATION OF LOAD LEVEL CHANGE, MAG. 40X)

8.0 CONCLUSIONS

The manufacturing methods and technology has been established in which ten foot helicopter main rotor blade spars of the UH-60A BLACK HAWK configuration has been successfully fabricated by cold brake forming titanium sheet material into an elliptical pre-form shape, joining the preform by the continuous seam diffusion bonding process, and hot creep forming the bonded spar tube into the required airfoil contour. Fatigue testing has ascertained that continuous seam diffusion bonding has fatigue strength characteristics well in excess of maximum flight stress of the BLACK HAWK aircraft. The program, therefore, has demonstrated that continuous seam diffusion bonding CSDB is a viable joining process and has potential production relevance for helicopter main rotor blade spars and in other similar joining applications.

Scale-up to full size, twenty-five foot spars will be required in order to determine a production cost basis. However, due to the ease in inspectability as related to absence of the weld bead; to minimal process controls associated with the CSDB process and with the associated reduction in rejection rate, it is anticipated that, if development of the full size, twenty-five foot spar was complete and the facility was on-line, the cost savings of production CSDB spar tubes compared to PAW spar tubes would be approximately 10%.

Additional efforts will be needed during the scale-up phase to refine tooling design in order to eliminate future occurrence of any interaction between the titanium pre-form and the external wheel electrode or the internal mandrel electrode.

9.0 RECOMMENDATIONS

It is recommended that, the CSDB process be considered as a viable alternate fabrication procedure for blade spars as well as other similar joining applications on Ti-6Al-4V aircraft structures. Although encouraging results have been obtained in the current contract effort, pursuit of the follow-on or the originally proposed Phase II effort of the current contract for application of CSDB spars for the UH60A helicopter is not recommended at this time because of the following reasons: (a) A substantial capital investment has already been committed to production plasma arc welding equipment and a significant amount of full scale qualification data on plasma arc welded spars has now been obtained for the BLACK HAWK, UH60A helicopter. (b) A significant additional dollar commitment would still be required to scale-up the CSDB process to produce full-size, twenty-five foot long production spars and obtain the qualification data necessary to be able to incorporate CSDB spars into production. (c) The time frame of the existing production schedule for the UH60A helicopter with respect to that time at which CSDB spar implementation could be accomplished is such that it is not expected that a substantial return on investment would be realized at this point in time.

REFERENCES

(a) Bonassar, Maron J. and Lucas, J., "Continuous Seam Diffusion Bond Titanium Spar Evaluation," Army Materials and Mechanics Research Center Report, AMMRC CTR 74-37 (April 1974). Contract Number DAAG46-72-C-0175.

(b) Gulden, M.E., Metcalfe, A.G., and Thorsrud, E.C., "Parametric Study of Diffusion Bonded Butt Joints," Army Materials and Mechanics Research Center Report, AMMRC CTR 75-29 (November 1975). Contract Number DAAG46-75-C-0040.

(c) Regalbuto, John A., "Nondestructive Testing Techniques for Diffusion Bonded Titanium Structures," Army Materials and Mechanics Research Center Report, AMMRC CTR 73-53 (December 1973). Contract DAAG46-73-C-0067.

(d) Thorsrud, E.C., "CSDB Process For UTTAS Helicopter Spars, Pre-form Numbers 7 and 8, Army Materials and Mechanics Research Center Report RDR189 (November 16, 1977). Contract Number DAAG46-77-M-1810.

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APPENDICES

Appendix A - Continuous Seam Diffusion Bonding Pre-form Specification

Title: Specification for Fabrication of Titanium Pre-forms for CSDB of BLACK HAWK Spars

Scope: The purpose of this specification is to provide requirements for the fabrication of pre-forms from titanium 6Al-4V alloy sheet material for butt joining by Continuous Seam Diffusion Bonding, CSDB, of BLACK HAWK spars.

Specification: SS-8455, Ti Alloy 6Al-4V Sheet, Strip and Plate

MIL-T-9046, Ti and Ti Alloy Sheet, Strip and Plate.

Requirements: The following requirements shall be used for the fabrication of pre-forms to be joined by CSDB for BLACK HAWK spars:

1. The pre-form shall be fabricated from titanium 6Al-4V alloy sheet material with the following requirements: A sketch of the titanium sheet is provided in Figure A1.

Length of Sheet	300 $\pm$ 1 inches
Width of Sheet	16.364 $\pm$ .010 inches
Thickness of Sheet	.145 $\pm$ .005
Edge Squareness	1° within .002 inch
Surface Roughness	63AA max
Straightness of Edge	.005 inch max

Note: The longitudinal machined edges of the titanium sheet are NOT to be deburred or rounded. DO NOT BREAK SHARP EDGES. After machining, the sharp, knife edges are to remain and shall be protected with an edge covering, e.g., vinyl channel material.

2. After brake forming the titanium sheets, the pre-forms shall conform to the configuration depicted in Figure A2 and shall be in accordance with the following criteria.

2.1 Unclamped pre-form requirements;

Gap (Distance between surfaces to be bonded)	7/8 to 1 inch
Symmetry (centerline of width dimension to coincide with the midline of the Gap)	Within 3/16 inch max
Internal Height Dimension	4-½ ± ½ inch
External Width Dimension	6-½ ± ¼ inch
Width of free edge flats	1 to 1.1 inch
Width of flat at base	½ inch min each side of centerline of the width of the sheet
Flatness of free edge flats	Within .010 inch in any six inches
Mismatch of free edge flats	1/8 inch max
Straightness (Longitudinal Direction)	1 inch max in 10 feet 3 inch max over 300 inches

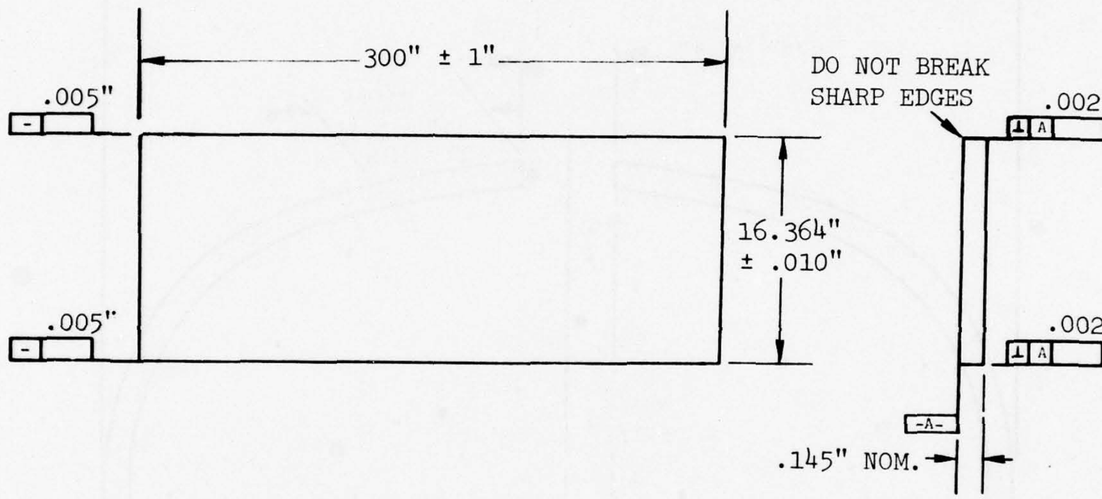


FIGURE A1. TITANIUM 6A1-4V SHEET MATERIAL FOR CSDB PRE-FORMS.

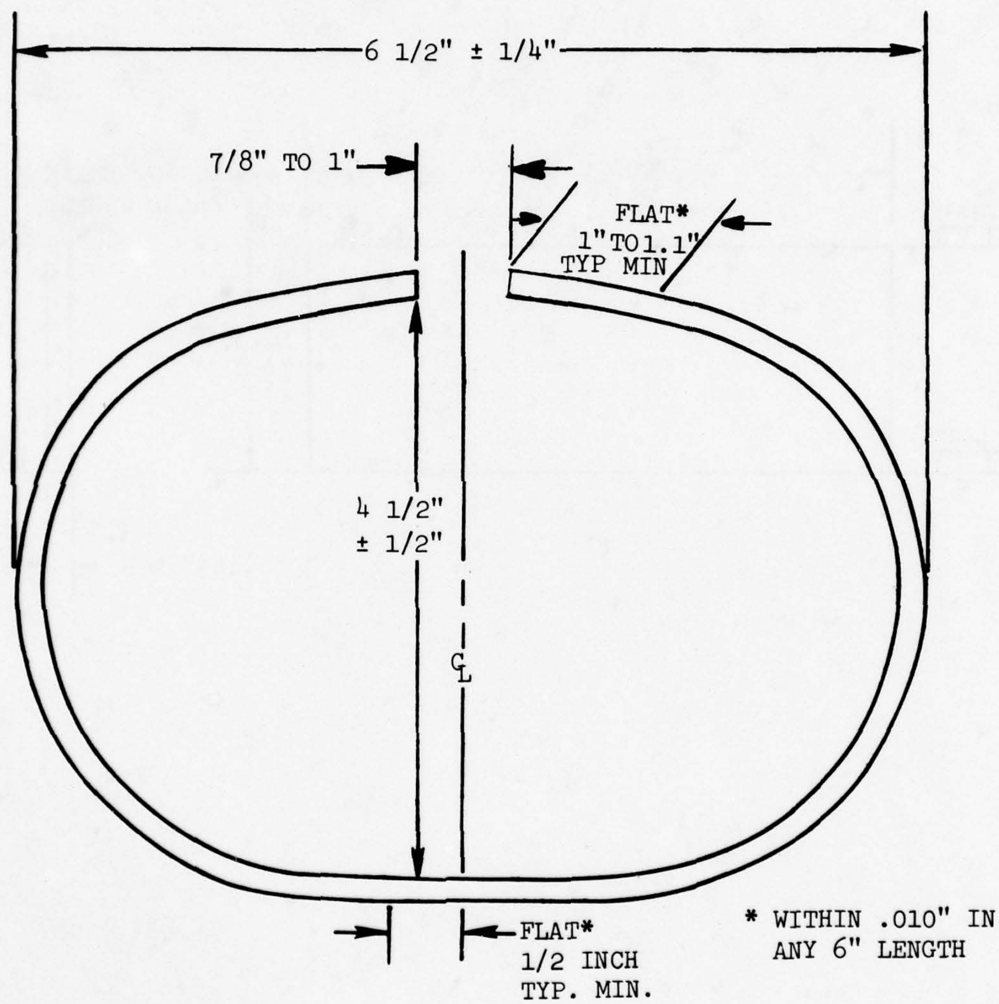


FIGURE A2. TYPICAL PRE-FORM CONFIGURATION.

Appendix B - Cleaning Procedure for Continuous Seam Diffusion Bonding Components

Materials

- Solvent, Metriclene MF, or equivalent
- Solvent, ND-150 solution, or equivalent
- Alkaline cleaner, Oakite 77, or equivalent
- Acid, Nitric 42° Baume (Fed. Spec. 0-A-88)
- Acid, Hydrofluoric, 70% (Fed. Spec. A-H-795)
- Water, demineralized (commercial grade)

Method

1. Solvent wash, using ND-150 solution of Metriclene M-4 as required to remove all mill marks, inks and dyes. (Chrloinated solvents will not be used on titanium parts.)

2. Immerse in the alkaline cleaner and allow to remain for minimum of 5 minutes -

   a. Solution - 6 to 10 ounces of Oakite 77 per gallon of water maintained at 160-180°F.

   b. Immersion rinse and repeat alkaline cleaner cycle until a "water break free" surface condition is achieved.

3. Rinse - a thorough rinsing in water is required.

4. Immerse in nitric-hydrofluoric acid solution and hold as required to loosen scale, oxides and discoloration.

   a. Solution - 3 to 5 percent hydrofluoric acid by volume, plus 27 to 32 percent of nitric acid by volume in water maintained at a temperature of 130-140°F.

   b. Immersion time limits vary with solution conditions, long durations may be used as long as a detrimental etching is avoided.

5. Rinse - clear water

   a. Air-water blasting may be used to remove scale, oxides and discoloration.

6. Immerse in nitric acid solution, hold as required to loosen all smut and oxide residues.

   a. Solution - 40 to 50 percent solution of nitric acid by volume in water, maintained at 140-180°F.

7. Immersion rinse in clean water and follow with air-water blasting to remove all smut and other residues.

8. Rinse - demineralized water

9. Bake until dry - 250 $\pm$ 50°F.

10. Package

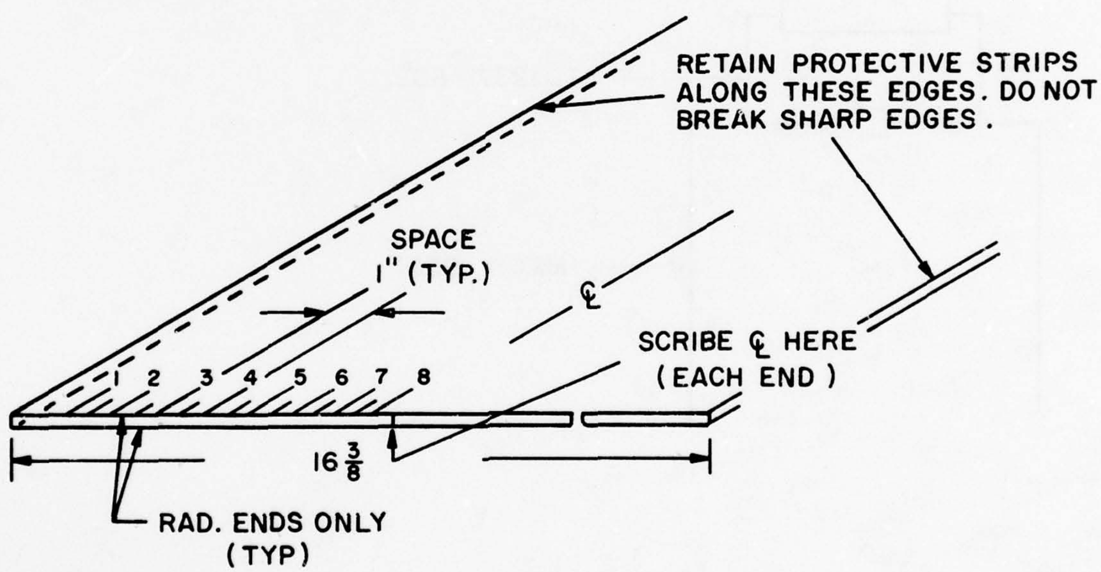
    a. Do not handle without clean white gloves.

    b. Wrap in paper until used.

    NOTE: Clean only that quantity of parts that can be bonded in a single shift.

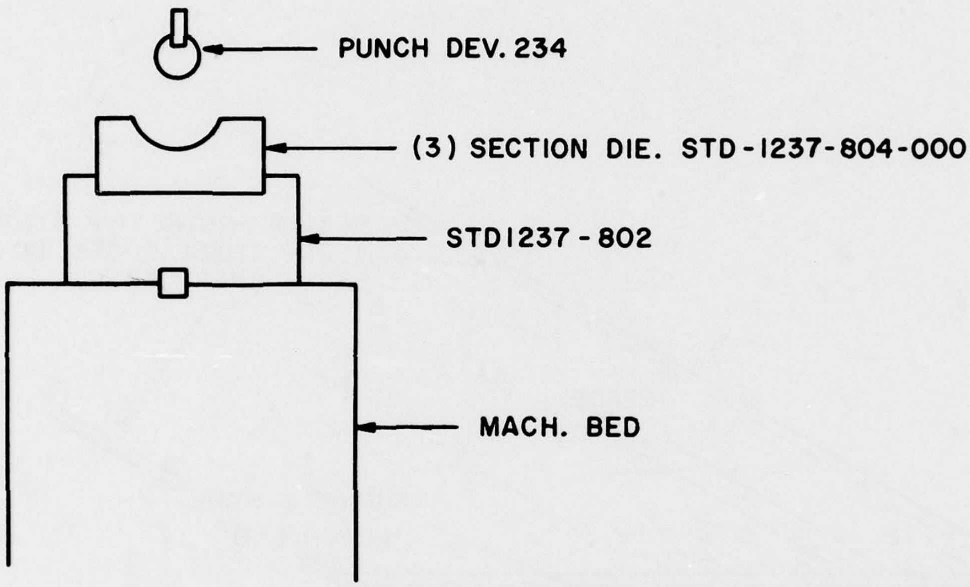
Appendix C - CSDB Brake Forming Operation Sheets

010 Place titanium sheet on knee supports in front of brake press.
020 Check sheet for radius on both ends (to keep sheet from cracking).
030 Check sheet for any impression stamping (hold for further info).
040 Mark off ends of sheet with ink marker per sketch below.
050 Lines are every 1/2 inch apart starting from the edges and going to the centerline. Scribe on thickness dimension of sheet as shown. DO NOT scribe on O.D. or I.D. of pre-form.
060 Retain protective strips along longitudinal length of sheet during brake forming operation.



070 Install dies on brake as shown.

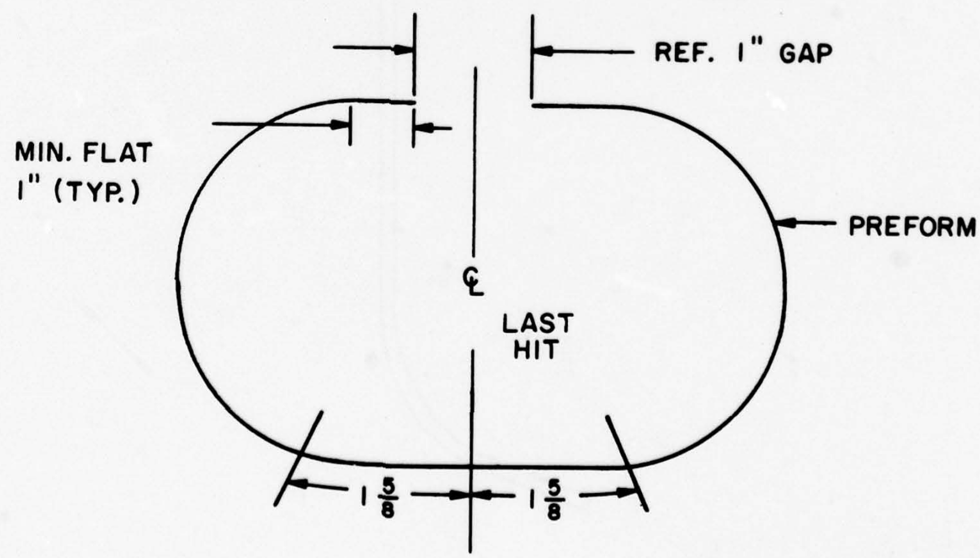
Note: Shim dies as required. Contour in die to be parallel with punch.
Prove by squashing 1/8 inch aluminum wire.

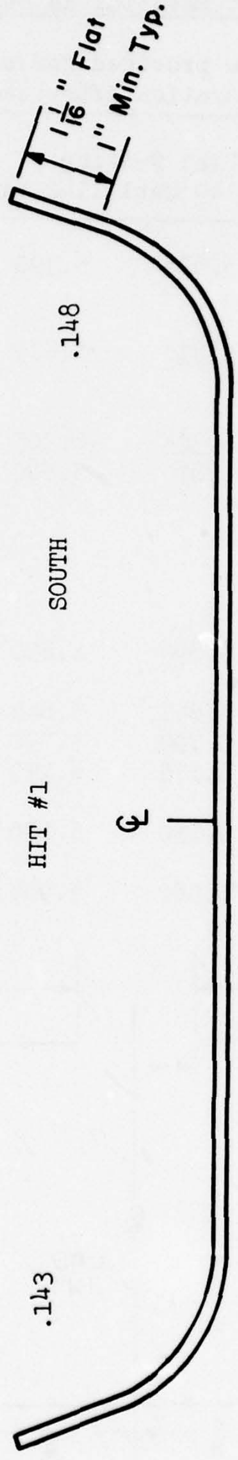


.080 Brake Form Titanium Sheet Material as Described Below:

Note: Sketches of each hit are provided for use as a guide and illustrate sheet configuration after each hit.

Hit No.	Distance Punch to Edge	Dial Setting .149 Matl	.142 Matl	Remarks
1	2.2	5.805	5.790	Use hinged stops at 5-5/16 from front of die.
2	2.6	5.890	5.875	Clamp angles at 5-5/8" on bottom of sheet.
3	3.1	6.305 5.875	6.305 5.860	Clamp angles at 7" on bottom of sheet for partial form, then clamp at 6-1/2 after hit check for 7°-8° closed.
4	5.2	5.890	5.890	Clamp angles on bottom of sheet on.
5	4.5	5.845 5.790	5.845 5.790	Form to 1.85 rad template.
6	6.0	6.170	6.170	Form to 1.85 rad template.
7	6.5	6.130	6.130	Form to 1.85 rad template.
8	See Sketch*	5.980	5.980	Form to 1.85 rad template.




1 1/16" Flat
1" Min. Typ.
.148
SOUTH
HIT #1
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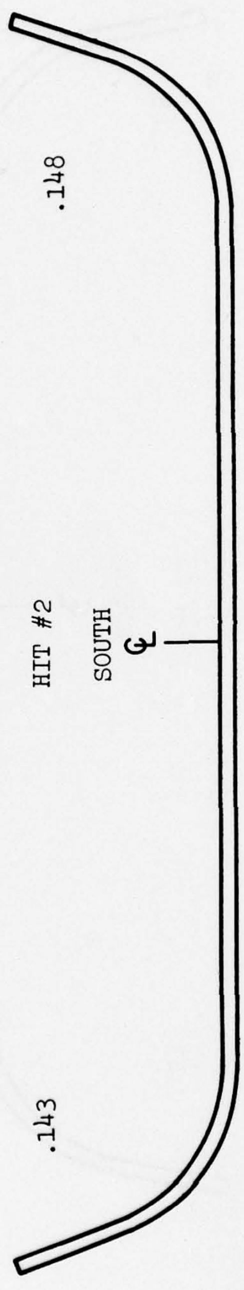
.143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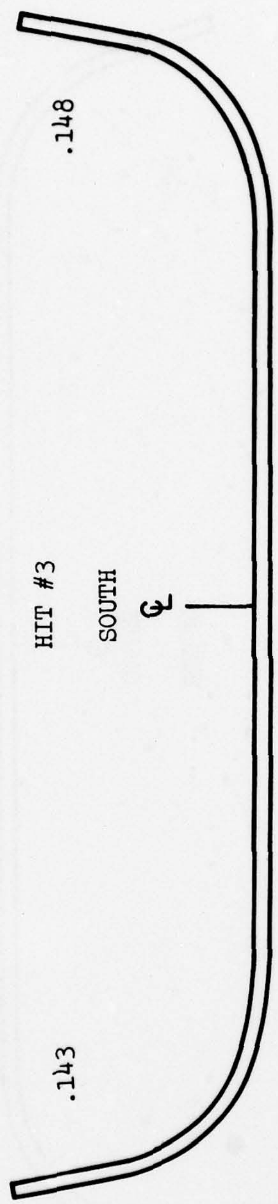
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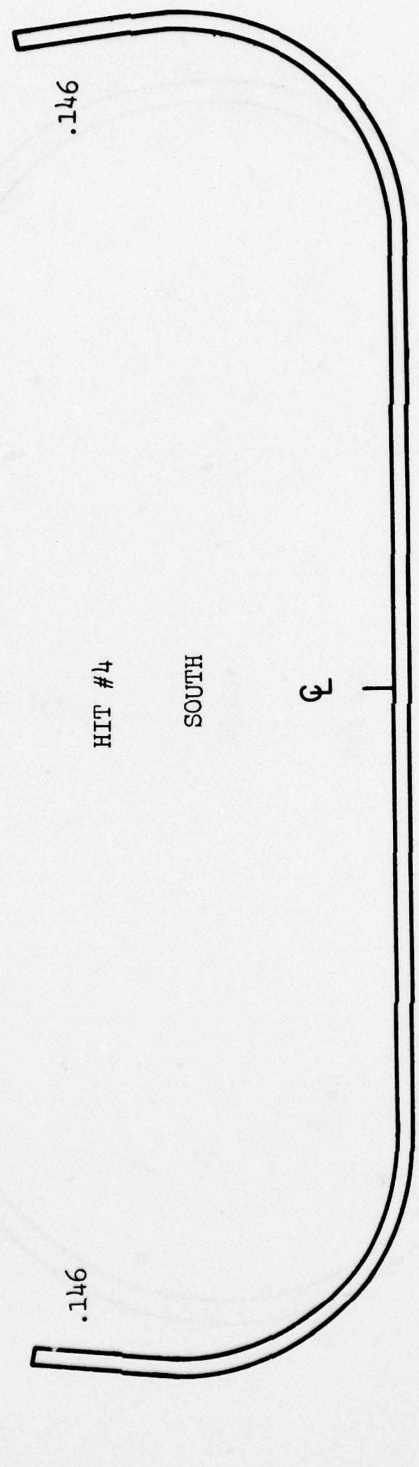
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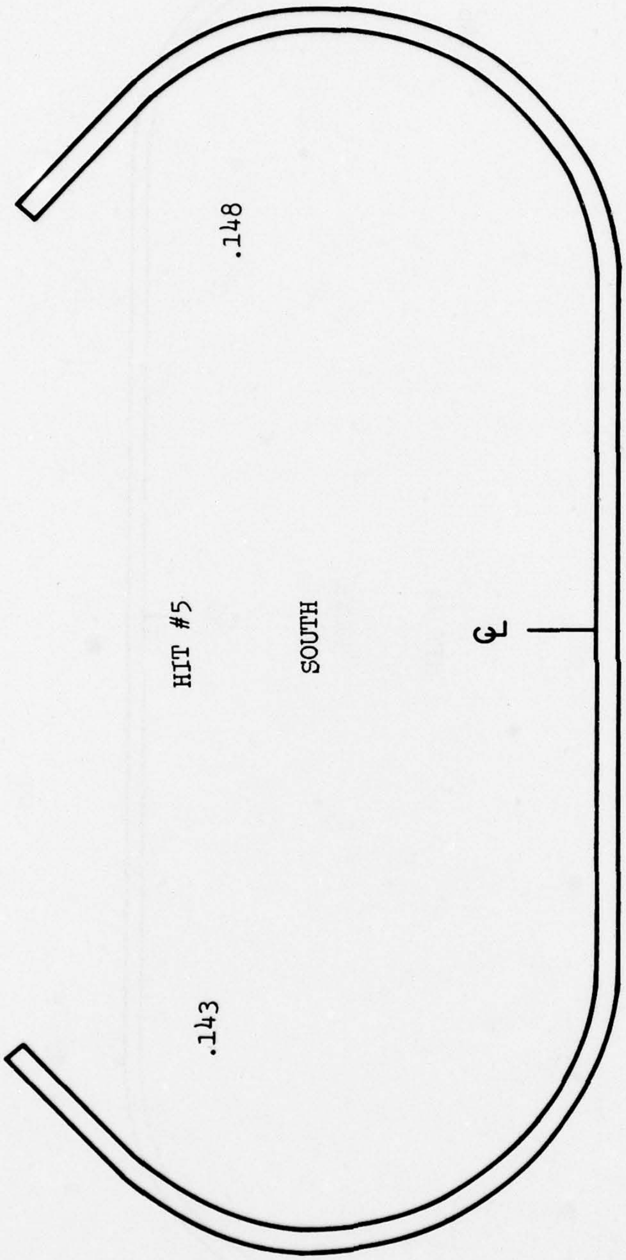
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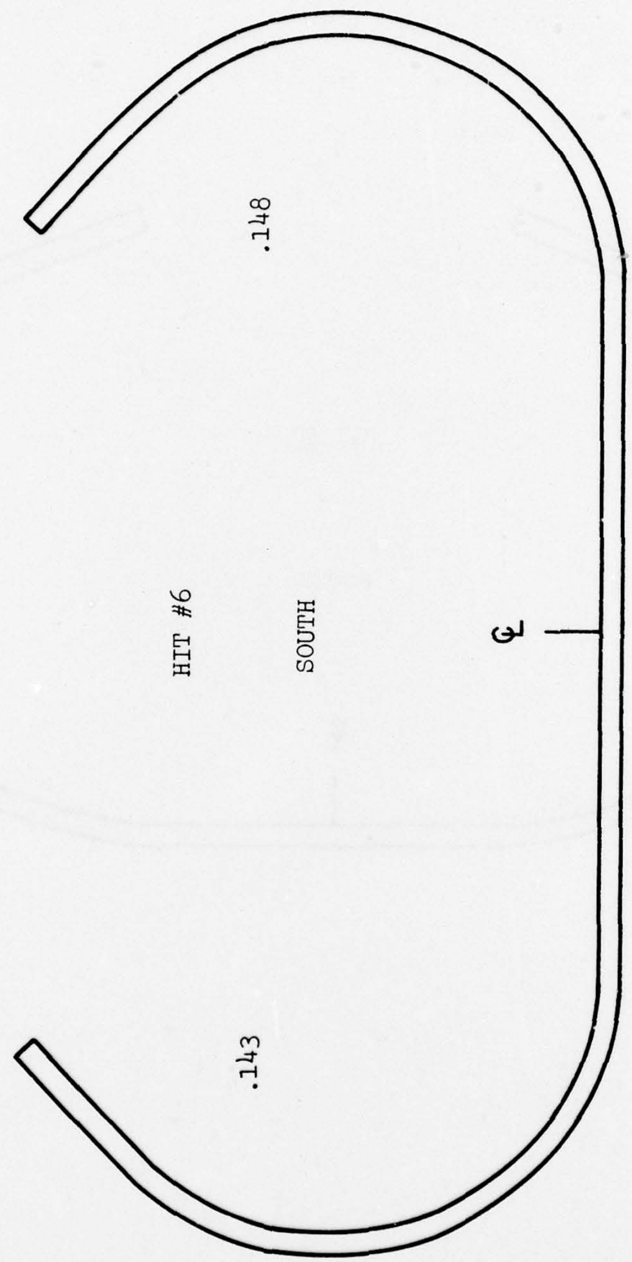

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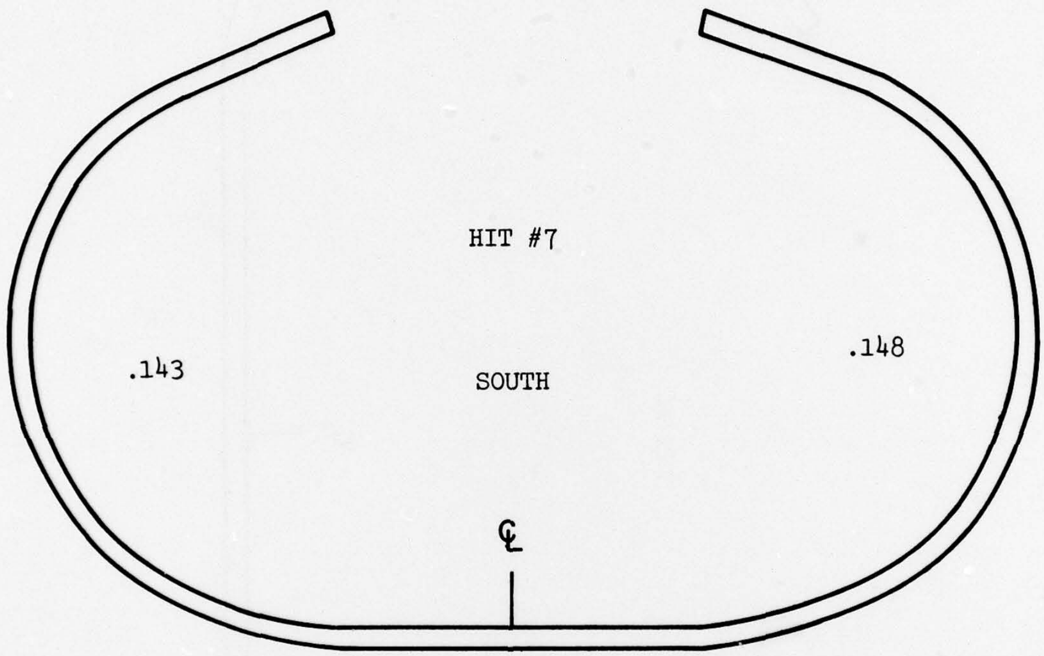
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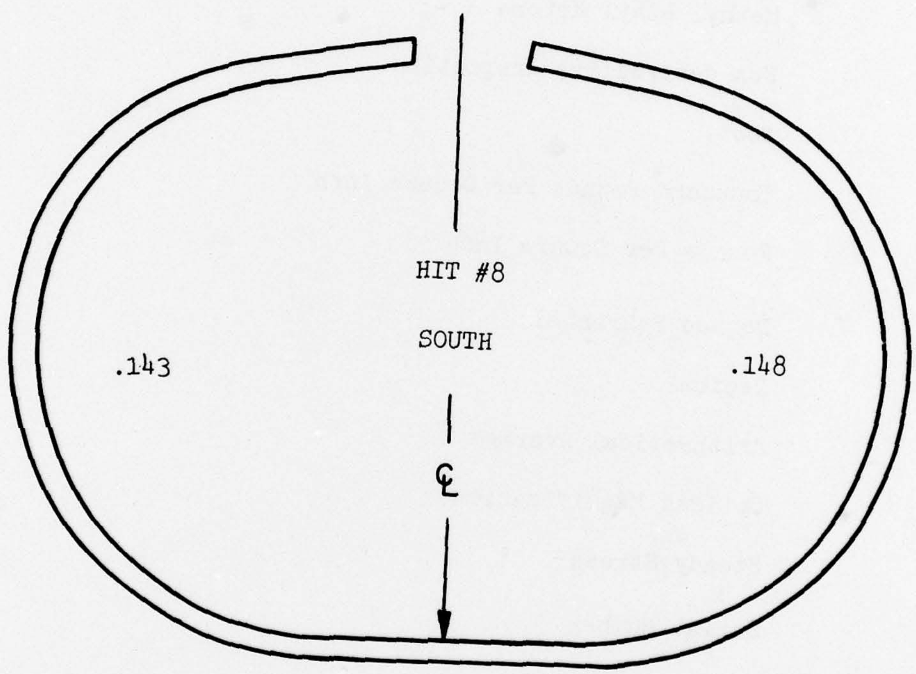

HIT #8
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LIST OF SYMBOLS

CSDB	Continuous Seam Diffusion Bond
MM&T	Manufacturing Method and Technology
PAW	Plasma Arc Weld
Ti-6Al-4V	Titanium Alloy containing 6% aluminum 4% Vanadium as major alloying elements
MEK	Methyl Ethyl Ketone
NDI	Non-destructive Inspection
ft	foot
KSI	Thousand Pounds Per Dquare Inch
psi	Pounds Per Square Inch
^oF	Degree Fahrenheit
db	Decibel
AA	Arithmetical Average
X	Optical Magnification
f_s	Steady Stress
S/N	Serial Number
CPS	Cycle per second
H_z	Hertz
lbs	Pounds

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Maron J. Bonassar and John J. Lucas
Sikorsky Aircraft Division of
United Aircraft Corporation
Stratford, Connecticut 06602

Technical Report AMMRC CTR
illus-tables
Contract DAAG46-76-C-0016
D/A Project:
Final Report: October 1, 1975 to September 30, 1978

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Key Words

Titanium Alloy
Rotor Spars
Diffusion Bonding
CSDB
Joining
Helicopter Blade

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